The Thesis Committee for John Marshall Swartz
Certifies that this is the approved version of the following thesis:

Seismic and morphologic analysis of the Gulf of Alaska Yakutat margin: evidence for recent trough mouth fan growth

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

Sean P.S. Gulick

Ginny Catania

John Goff

Seismic and morphologic analysis of the Gulf of Alaska Yakutat margin: evidence for recent trough mouth fan growth

by

John Marshall Swartz, B.S.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Geological Sciences

The University of Texas at Austin

August 2014

Abstract

Seismic and morphologic analysis of the Gulf of Alaska Yakutat margin: evidence for recent trough mouth fan growth

John Marshall Swartz, M.S. Geo. Sci.

The University of Texas at Austin, 2014

Supervisor: Sean P.S. Gulick

The active St. Elias Orogen in southern Alaska was created by collision of the offshore Yakutat Terrane with North America. These mountains exhibit the highest coastal relief in the world and also are home to temperate tidewater glaciers, one of the most powerful erosive agents known. Glaciation in Southern Alaska has occurred since the Miocene, but climatic shifts associated with the intensification of Northern Hemisphere glaciation at ~2.5 Ma and the mid-Pleistocene transition at ~1 Ma have led to drastic increases in glacial erosion and associated offshore sediment transport and deposition. The Yakutat continental shelf has hosted ice streams during glacial advances since the mid-Pleistocene, but it is only recently that ice has reached the continental shelf edge itself. Quantitative morphologic analysis finds significant variability along the slope, with an relatively gentle gradient trough mouth fan building off the Yakutat Sea Valley, a shelf-crossing glacial trough, due to massive sediment supply from the heart of the St. Elias Orogen, while farther to the east the extremely steep continental margin is heavily gullied and sediment bypasses the slope reaching the offshore Surveyor fan.

Seismic stratigraphy indicates that ice streams first reached the shelf edge with the mid-Pleistocene climate transition, a shift from 41 ka to 100 ka glacial-interglacial climate cycles. This increase in glacial durations allowed not only the ice to sustain advances to the shelf edge, but led to amplified erosion and climate-tectonic feedback effects.

Table of Contents

CHAPTER 1: QUANTITATIVE MORPHOLOGY OF THE YAKUTAT MARGIN

Abstract

Glaciated continental shelves are host to numerous morphologic features that help understand past glacier dynamics. Southeastern Alaska is home to the St. Elias Mountains, an active orogen being impacted by temperate marine glaciers. During glacial periods ice streams advance across the continental shelf, carving shelf-crossing troughs that reach the shelf edge. We use high-resolution multibeam data to develop the relationship between two troughs, the Yakutat and Alsek Sea Valleys, and associated continental slope morphology. The shelf and slope geomorphology can be divided into statistical groupings that relate to the relative balance of erosion and deposition. Our analysis indicates that only the Yakutat system has been able to build an incipient trough-mouth fan. The extreme sediment supply from this region was able to overwhelm the steep initial topography of the transform margin, while farther to the east sediment slope-bypass dominates. This analysis provides an extreme end member to existing studies of temperate glaciation along continental margins. The unique interplay between rapid uplift due to ongoing collision and the massive erosion caused by temperate glaciers in a coastal system with extremely high precipitation provides for sedimentary flux far greater than other systems and thus allows for formation of a trough mouth fan in spite of a tectonically generated steep slope.

1. Introduction

High-latitude glaciated margins have broad morphologic variability reflecting a combination of climate, tectonics, and pre-existing margin physiography [*O'Grady et al.,* 2002; *O'Cofaigh et al.,* 2003]. During glacial advances marine-terminating glaciers can cross the continental shelf and route large volumes of sediment to the outer shelf, slope, and basin. Analysis of resulting sedimentation and morphology has been an important tool in understanding past glacial dynamics as well as the construction and evolution of continental margins [e.g. *Vorren and Laberg,* 1997; *Solheim et al.,* 1998; *O'Grady et al*., 2002; *Dowdeswell et al.,* 2006; *O'Cofaigh et al*., 2012]. Identifying variations in high-latitude morphology across glacial systems and regions can help to assess the relative importance of each controlling factor and lead to a better understanding of glaciated margin development.

Ice-crossing continental margins can take various forms during glacial advances, often forming fast flowing ice-streams [*Stokes* and *Clark,* 2001; *Dowdeswell et al.,* 2006]. Erosion by the ice stream leads to rapid and high sediment delivery to the ice edge, which is subsequently mobilized and distributed down the slope and beyond by mass-flow processes [e.g. *Alley et al.,* 1989; *O'Cofaigh et al.,* 2012]. Locations of paleo-ice streams are commonly associated with a type of slope sedimentary deposit known as a trough-mouth fan (TMF), so named as they occur at the mouth of an erosional cross-shelf trough [e.g. *Vorren* and *Laberg,* 1997*; Dowdeswell et al.,* 2008; *Batchelor et al*., 2013]. TMFs can be identified by seaward bulging bathymetric contours and other indicators of shelf edge progradation, and often have gentler slopes than the surrounding margin [*Vorren et al.*, 1998; *O'Cofaigh et al.,* 2005; *Dowdeswell et al.,* 2006].

In the Gulf of Alaska eight shelf-crossing sea valleys have previously been observed and interpreted as hosting focused ice flow during glacial advances [*Carlson et al.,* 1982; *Powell and Cooper,* 2002**;** *Berger et al.,* 2008]. The Alsek and Yakutat Sea Valleys (Fig. 1), created by the Alsek District and Malaspina-Hubbard glacial systems respectively, appear to be long-lived cross-shelf troughs that are reoccupied during glacial advances, most recently during the last glacial maximum (LGM) when ice streams advanced to the shelf edge [*Elmore et al.,* 2013].

Glaciation in this region began near the end of the Miocene and coincided with ongoing orogenesis of the St. Elias Mountains in S.E. Alaska [*Rea* and *Snoeckx,* 1995; *Berger et al.,* 2008]. The sea valleys themselves were likely created when glaciers reached the ocean sometime during the Pleistocene, delivering large volumes of sediment across the continental shelf and building the deep sea Surveyor Fan [*Lagoe et al.,* 1993**;** *Lagoe* and *Zellers*, 1996; *Worthington et al.,* 2010; *Reece et al.,* 2011]. The fan is fed by a complex network of channels and gullies along the Yakutat margin that route significant volumes of sediment past the continental slope [*Bruns and Carlson,* 1987; *Dobson et al.,* 1998]. However, the slope morphology itself has remained poorly studied due to limited data. Recent high-resolution multibeam bathymetry [*Gardner et al.,* 2006] allows, for the first time, a quantitative characterization of slope morphology associated with the Yakutat and Alsek paleo-ice streams.

Here we focus on developing the relationship between shelf-edge glaciation and continental slope morphology. This paper provides the first quantitative morphologic analysis of the Gulf of Alaska Yakutat margin using two approaches: (1) large-scale geomorphic characterization, and, (2) statistical analysis of gullies and channels along the continental slope. We identify significant variations in large-and-small scale morphology and discuss their relation to the Yakutat margin's unique interplay between active tectonics, temperate glaciation, and transform margin architecture. We place the Gulf of Alaska into a global context as an extreme end-member of temperate glaciated continental margins, and suggest implications for the relative importance of glacial source dynamics and sediment supply.

2. Study Area

We focus on the portion of the Yakutat margin bounded to the west by the Pamplona zone, the deformation front of the ongoing subduction of the Yakutat Block [*Worthington et al.*, 2010; 2012], and to the east by the Fairweather Ground, a basement related bathymetric high [*Plafker et al.*, 1987] (Fig. 2). The Yakutat Block is a 15-25km thick oceanic block overlain by 5-7.5km of Cenozoic sediments [*Plafker et al.,* 1994; *Christenson et al.,* 2010; *Van Avendonk et al.,* 2013] (Fig. 3). Between the Yakutat Block and the Pacific Plate is the Transition Fault, a transform fault that coincides in most areas with the margin slope-rise break. Although this boundary controls the slope break, there has been little lateral movement since 5-6 Ma, and the Pacific Plate and Yakutat Terrane are in effect moving together [*Gulick et al*., 2007; 2013].

The Surveyor Fan overlies most of the Gulf of Alaska abyssal plain [*Rea and Snoekx,* 1995]. Modern morphology of the fan is predominantly controlled by the Surveyor and Chirikov channel systems. The Surveyor Channel is over 700km long, and its upper section is composed of three main tributaries that link the Yakutat Block margin to the abyssal plain: the Icy, Yakutat, and Alsek Legs [*Carlson et al.,* 1996; *Reece et al*., 2011] (figs. 1, 2). Icy Leg is comprised of Icy Leg East and West and both of which appear to be associated with the continental slope west of the modern Yakutat Sea Valley (YSV), but with no obvious linkage to a modern glacial sea valley. The modern Yakutat Leg is a wide channel that appears closely linked to the YSV while farther to the east is the Alsek Leg, a system that directly links to the modern Alsek Sea Valley (ASV) (figs. 1, 2).

3. Data and Methods

We use two bathymetry sources to provide gradient and depth data. The highest resolution (100m cell size) dataset is a 162,000 km^2 multibeam sonar grid collected aboard the R/V *Kilo Moana* in 2005 using a Kongsberg EM120 (12 kHz) echo sounder with a 150° swath width [*Gardner et al*., 2006; *Gulick et al.*, 2007]. These data were collected along the base of the slope and only intermittently cover depths shallower than 1000m. Coverage of the continental shelf and upper slope is provided by low-resolution bathymetric contours [*Atwood et al*., 1981] digitized and gridded to a 1km cell-size raster. Raster grid manipulation and analysis was performed using ArcGIS 10.2 with spatial analyst and 3D analyst extensions (http://www.esri.com). The bathymetric grids were projected using an Alaskan Albers Conformal Conic projection for spatial analysis.

Seafloor gradient values were created using the base bathymetric grid. This raster provides the maximum change between a cell and its nearest neighbors (degrees), and allows for identification of steeply- and gently-sloping areas of the seafloor. A flow drainage network was also constructed from the gradient values. This set of vectors indicates the path that a fluid would flow over the surface, and is used to identify channel systems and the catchment regions that contribute to them. Finally, a seafloor aspect map was created identifying the compass direction that each cell of the bathymetric grid is oriented towards. This map allows for differentiation between along-slope and down-slope bathymetric features.

3.1. Large-scale geomorphic characterization

We divided the Yakutat continental margin into five zones (A-E) of similar-sized area that roughly parallel the continental shelf (Fig. 2). Each zone boundary was qualitatively chosen based on large morphologic features, such as glacial cross-shelf troughs, and natural boundaries in the flow drainage network (Fig. S1). Using the procedure of *Brothers et al.*, [2013], depth values as well as co-registered gradient and aspect values were extracted for all grid-cells within each zone. The resulting datasets were filtered to exclude grid-cells with an aspect beyond ± 0.5 standard deviations of the slope mean aspect (Fig. S2). Gradient data were then binned into 20-m depth intervals and the gradient average calculated [*O'Grady et al.*, 2000; 2002; *Brothers et al.,* 2013]. Overall summary statistics for each zone were computed, as well as for slope and rise subsets.

Similarity of large-scale morphology was assessed using two methods: (1) a Welch's analysis of variance (ANOVA), with no *a priori* assumptions about the variance of the underlying populations, applied to overall zone gradients followed by multiple comparison procedures (MCP) [*Welch et al.,* 1951, *Tukey,* 1977]; and (2) a maximum likelihood factor analysis [*Reyment* and *Joreskog,* 1993; *O'Grady et al.,* 2000] applied to the depth-gradient distributions. Common factor analysis allows for potential relationships to be identified within a dataset. Continental margins have often been found to have a high degree of variance explained by factor-1, which is thought to relate to a common shape of a flat shelf, an angled slope, and then a flat rise, while factor-2 likely describes variations between margins of the common shape, e.g. a relatively steep or a relatively gentle slope [*O'Grady et al.,* 2000]. The resulting factor-2 values of this study were compared with zone gradient maxima to assess potential statistical groupings [*O'Grady et al.*, 2000; 2002; *Brothers et al.,* 2013]. The groupings identified by ANOVA testing and factor analysis are referred to as groups and types, respectively.

3.2. Gully and channel analysis

Gully formation and evolution on glaciated margins have been attributed to a range of processes including sediment gravity flows, oversteepening and failure of the margin, and discharge of sediment-laden subglacial meltwater [e.g. *Dowdeswell et al.,* 2006; *Noormets et al.,* 2009; *Gales et al.,* 2012; *Livingstone et al.,* 2013]. Quantitative analysis of gully parameters helps to understand the active processes responsible for their creation [*Gales et al.,* 2012]. Gully relief appears to be influenced by the gradient and shape of the continental slope, with steep linear slopes having lower gully relief to the base of slope while Gaussian slopes have a relatively constant gully relief [*Goff*, 2001]. Erosional mechanisms of gully formation can be influenced by slope and environmental characteristics that lead to a characteristic morphology, such as high gradient slopes generating dense water/sediment gravity flows and continental shelf cold dense water formation cutting back into the shelf edge [*Noormets et al.,* 2009; *Micallef and Mountjoy,* 2011].

To understand the nature of gully formation in the Gulf of Alaska, we analyzed a limited range of gully and channel parameters using across-slope depth profiles extracted from the middle slope rather than the upper slope due to a lack of consistent near-shelf edge bathymetric coverage. The depth of the slope/rise break shallows to the east, and so in Zones A and B these profiles parallel the 2000m contour, while in Zones C, D, and E the profiles parallel the 1500m contour (Figs. 2, 4). We identified each gully, channel, or mass-wasting feature with a relief greater than 5m from these profiles [*Noormets et al.,* 2009; *Gales et al.*, 2012; 2013]. Parameters including width, depth, cross-sectional shape (Fig. 5), and feature density (number of features/length of profile) were calculated for all gullies.

We approximate the cross-sectional shape of each gully using the General Power Law (GPL) program [*Pattyn and Van Huele*, 1998; *Gales et al.,* 2012], which finds a best fit for a given cross-sectional profile using:

$$y - y_0 = a|x - x_0|^b$$

where x and y are horizontal and vertical coordinates along the depth profile, x_0 and y_0 are coordinates of the profile minimum, and a and b are constants. The b value is a measure of cross sectional shape, with 1 forming a V-shape and 2 forming a parabola, or U-shape. Values <<1 are shapes with convex upward sides, while values >> 2 approach a box. Gullies are categorized as b values >1.5 are U-shaped, while b values < 1.5 are V-shaped. The GPL also provides an error value of the fit between the given profile and the resulting shape, r^2.

4. Results and Analysis

Three general margin shapes (types 1-3) were identified by factor analysis, while Welch ANOVA testing indicated that the zonal gradient distributions fall into three distinct groups (groups A1-A3). We identified a total of 186 gullies and mass wasting features along the mid-slope region (1500-2000m depth) of the study area.

4.1. Margin observations and shape

Using factor analysis we find that two factors explain 80.2% of the observed variance in margin depth-gradient distributions. Factor-2 loadings (39% explained variance), plotted against maximum gradient [*O'Grady et al.*, 2000; *Brothers et al.,* 2013], identify three potential groups, from west to east: Type 1 (zones A, B), Type 2 (zone C), and Type 3 (zones D, E) (Fig. 6).

4.1.1. Type 1: Zones A & B

This "Type 1" shape is characterized as having a relatively consistent, wide (25-35km) slope from the shelf break to the slope-rise transition (Fig. 7). A slight increase in gradient is observed along the base of slope: in zone A this coincides with the location of a Transition Fault related basement high, known as the Yushin Ridge, while we do not observe obvious structures in zone B. The slopes of both zones have prominent outward bulging bathymetric contours (Fig. 2). Each zone's slope is relatively gentle (A- 8.5° ± 3.1°, B- 9.0° ± 2.1°) until near the slope-rise break.

While the extant YSV cuts across the shelf of zone B and reaches the shelf break, data coverage does not exist to identify small-scale features directly at shelf-slope transition. The western side of Zone A has numerous linear gullies and chutes that feed into the Icy Legs East and West, while to the east the remainder of Zone A and all of Zone B feeds into the upper Yakutat leg. The slope channels of Zone B are not homogenous, and in many cases resemble a series of cascading chute-like sediment deposits. The slope channels of both zones A and B appear to link to the basin floor channel systems that feed the Surveyor Fan, but these linkages appear relatively shallow and have low-gradient channel walls (Fig. 2).

4.1.2. Type 2: Zone C

Type 2 consists solely of Zone C, which has a roughly symmetrical depth-gradient distribution (Fig. 7). No morphologic evidence exists for ice reaching the shelf break during the LGM in this region. A sharp shelf break at ~300m depth is followed by a steep (18.3° ± 7.2°) and narrow (~15km) slope until an abrupt slope break at 3200m depth that coincides with the Transition Fault. The slope is heavily gullied, with observed gully heads near the shelf break. However, there do not appear to be any significant active channels that lead to either the Yakutat or Alsek legs (Fig. 2).

4.1.3. Type 3: Zones D & E

Type 3 grouping characterizes zones D and E, and has a shape generally opposite to Type 1 (Fig. 7). A sharp shelf break at ~500m occurs in both zones, followed by a steep slope (16.6° ± 6.6° for Zone D, 21.9° ± 9.7° for Zone E). The narrow slope of zone E grades into a relatively steep and prominent gully incised rise (4.3° ± 3.8°) that is absent in Zone D. The ASV reaches the shelf edge in Zone D, while Zone E contains the Fairweather Ground, an exposed basement bathymetric high (*Plafker et al.,* 1987). Two large shelf-incising canyons are observed in the contours of Zone D, although exact parameters cannot be quantified due to low-resolution data coverage on the upper slope. These canyons each appear to be associated with slope-break fans (Fig. 2). In contrast to the zones of Types 1 and 2 (Zones A-C), the maximum average gradients (30.9° and 41.2°) are found in the upper slope, at depths of 1370m and 1570m. The slope gullies and channels of these zones lead to the Alsek Leg of the Surveyor Fan, and these Surveyor Fan feeder channels appear to be fairly active, with relatively deep thalwegs and steep channel walls (Fig. 2).

4.2. Average zone gradient

In order to assess the variability of margin steepness, the five zone gradient means were compared using a Welch ANOVA *F*-test and found to be significantly different ($p < 0.0001$). Tukey-Kramer MCP determined three statistically significant groups (Fig. 8): Group A1 (Zones A and B), group A2 (Zones C and D), and group A3 (Zones C and E). Zones A and B have nearly identical low mean gradients (7.7° ± 3.8° and 7.7° ± 3.5°), followed by Zone D (13.8° ± 8.4°), Zone C (15.8° ± 8.5°), and finally Zone E (18.1° ± 8.5°) (Table 1). Zone C cannot be distinguished between zones D and E on the basis of means testing, and is included in both groups A2 and A3 (Fig. 8).

4.3. Slope gullies and channels

We identified 186 gullies and channels across the extracted mid-slope profiles: 43 U-shaped ($b > 1.5$) and 143 V-shaped ($b < 1.5$). Gully distribution and spacing are not constant across all zones (Table 2), with Zone B having the widest spacing of 2.6 km averaged over with 22 gullies. The frequency distribution (Fig. 9) shows 50% of gullies are between 5 and 50m deep. Gully relief, divided by zone, was compared using a nonparametric Kruskal-Wallis rank sum test and found to be different ($p < 0.0001$). MCP identifies two distinct relief groups: G1 (zones A, B) and G2 (zones C, D, E). On average, G1 gullies are relatively shallow (36m) and wide (1760m) while group 2 gullies are quite deep (93.7m) and slightly narrower (1587m). The distribution of gully shape (U/V index) is relatively similar across all zones (Fig. 10). While U-shaped gullies tend to be shallow (median 29.2m) and V shape gullies deep (median 62.9m), the significant relief ranges make them difficult to distinguish statistically. Gully relief, classified by shape, was compared using a Wilcoxon rank sum test and was not found to be significantly different ($p < 0.063$).

5. Discussion

5.1. Significance of Yakutat margin morphology

Large-scale geomorphology is highly variable across the Yakutat Terrane, but the shape of the margin and the statistical differences in slope gradient as identified by ANOVA and factor analysis can help understand the drivers of these variations. Sediment flux plays an important role in glaciated margin development, with regions associated with convergent ice, or ice streams, being especially likely to undergo progradation due to high sediment accumulation [*O'Grady et al.,* 2002; *O'Cofaigh et al.,* 2012]. Studies of margins, both glaciated and unglaciated, have emphasized that pre-existing architecture can be a key factor in the modern morphology of a continental margin, with existingbedrock or tectonically controlled steep slopes leading to sediment bypass of the continental slope [e.g. *O'Grady et al.,* 2000; *O'Cofaigh et al.,* 2003; *Batchelor et al., 2013*; *Brothers et al.,* 2013]. The Transition Fault coincides with the slope-rise break across the Yakutat margin [*Christenson et al.,* 2010; *Gulick et al.,* 2013], and basalts have been dredged along the slope indicating exposed Yakutat basement near the Fairweather Ground [*Bruns et al.,* 1987; *Plafker et al.,* 1994]. The thick terrane basement and Transition Fault contributed to very steep initial margin conditions [*Christenson et al.,* 2010; *Worthington et al*., 2012], which have then subsequently been modified by sedimentary deposition and erosion.

During the LGM, as well as several previous glacial maxima, ice advanced across the shelf forming or re-forming the YSV to the shelf edge in Zone B [*Reece et al.,* 2011; *Elmore et al.,* 2013]. The seaward-bulging contours and low-slope gradient of Zone B indicates that this region has likely undergone progradation related to past shelf edge glaciation [e.g. *Pudsey* and *Camerlenghi,* 1998; *O'Cofaigh et al.,* 2003; *Stokes et al.,* 2006; *Batchelor et al.,* 2013]. That this apparent progradation has occurred in spite of the steep initial conditions of the margin suggest a very high sediment flux to the slope. Zone A also exhibits bulging contours in addition to having a nearly identical gradient and shape to Zone B, despite not containing a glacial sea valley visible in the current bathymetry [Figs. 2, 5, 6]. We interpret that this indicates ice flowing west of the present-day YSV during previous glacial advances, but that shelf sedimentation has since covered any previously created trough. Further investigation of this relationship would require seismic stratigraphic analysis that is beyond the scope of this paper.

East of Zones A and B the margin morphology changes significantly (Figs. 2, 5). Studies of other high-latitude margins have found that inter-ice stream regions have much lower basal erosion rates and consequently lower sediment flux compared to regions with ice streams [*Batchelor et al.,* 2013]. Zones C and E, which lie between the Yakutat and Alsek sea valleys, have no observed evidence of grounded ice near the shelf edge during the LGM (Fig. 1) [*Manley* and *Kaufman,* 2002; *Elmore et al.,* 2013]. Seismic analysis from [*Elmore et al.,* 2013] suggests the possibility of ice cover across the mid-shelf during late Pleistocene glaciations, but it is unknown whether these events reached the shelf edge. Both zones have extremely high slope gradients that are statistically indistinguishable from each other. Due to lower sedimentary input and a sharp tectonic control on initial slope morphology, these regions are likely dominated by erosional processes and slope sediment bypass. This steep and narrow margin morphology likely reflects the underlying architecture of the Yakutat Terrane, with only minor sedimentary overprint.

The ASV hosted an ice stream that reached the shelf edge as recently as the LGM (Fig. 2) [*Elmore et al.,* 2013]. Unlike the slope associated with the YSV, however, we observe no geomorphic evidence for progradation at this location (Fig. 2, 5). The slope gradient and margin shape are not significantly different from Zones C and E, despite recent shelf edge glaciation (Figs. 5, 6). The steep gradient and lack of progradation despite the presence of a paleo-ice stream, imply significant sedimentary bypass and erosion of the slope, as has been observed on other steep glaciated margins such as Greenland and the Antarctic Peninsula [*O'Cofaigh et al.,* 2004; *Dowdeswell et al.,* 2008].

The morphology of the numerous gullies and channels along the Yakutat margin helps to understand the active slope processes that led to their formation. We find two distinct statistical groupings, based on gully relief, that correspond to the regions of slope progradation and erosion previously observed through the large-scale morphologic characterization (Figs. 2, 7). Gully morphology is controlled by numerous processes including erosion by sediment gravity flows, such as turbidity currents, as well as small-scale slumping and mass wasting [*Harris and Whiteway,* 2011; *Gales et al.,* 2013]. The majority of these gullies are V-shaped, commonly attributed to dense fluid flow such as sediment laden meltwater, while the remainder are U-shaped and are likely due to small-scale mass wasting [*Simons* and *Senturk*, 1992; *Noormets et al.,* 2009; *Gales et al.,* 2012]. Alternatively, the U-shaped gullies could be dormant, their shape due to infilling of sediments.

Comparing gully relief and width helps to illustrate the difference between the zones of likely progradation (A-B) and those that appear to be dominated by erosion and sediment bypass (C-E) (Fig. 9). The depth of gully relief might be indicative of the relative age of the gully and channel systems, as subsequent glacial advances might fill in previously formed gullies [*Gales et al.,* 2013]. The significantly shallower gullies of Zones A and B might indicate that they are relatively recent, while the high relief gullies of Zones C, D, and E are likely to be older, longer lived features that continually act as sediment conduits during glacial maxima. Continually active gullies in these zones potentially explain the apparently more active and well-defined connection between the Alsek region and the Alsek Leg of the Surveyor Channel systems as compared to relatively inactive Icy and Yakutat legs of the Surveyor Fan [*Reece et al.,* 2011].

5.2. The role of sediment supply in TMF growth

We suggest that the slope progradation associated with the YSV is evidence for relatively recent TMF formation. Cofaigh et al. [2003] and Batchelor et al. [2013] identified several key factors for TMF formation and growth, including a: (1) long history of marine glaciation, (2) continental shelf composed of sedimentary layers, (3) large glacial catchment, (4) wide continental shelf, and (5) low gradient continental slope. The majority of these variables relate to the availability of sediments for ice stream erosion, while (5) is related to whether sediment will be able to accumulate along the slope and contribute to fan progradation.

Both the YSV and ASV regions meet the majority of these criteria. Gulf of Alaska glaciation began at ~5.5 Ma, with several distinct intervals identified [*Lagoe et al.,* 1993]. The most recent of these is glacial interval C at ~1 Ma, which is an increase in glaciation and erosion that likely relates to the mid-Pleistocene transition (MPT) from 41 k.y to 100 k.y. glacial cycles [*Clark et al.,* 1996; *Berger et al.,* 2008]. The continental shelf of the Yakutat margin is fairly wide, ranging from 70-100km (Table 1), and while the Yakutat Terrane itself is an oceanic plateau, it is overlain with a significant amount of non-glacial and glacial sediment, increasing from 1km in the area near the ASV to over 5km where the YSV crosses to significantly greater thicknesses farther west [*Worthington et al.,* 2010; *Van Avendonk et al.,* 2013] (Fig. 3).

The key difference between the ASV and YSV systems is likely the glacial catchment size and source dynamics. The Malaspina-Hubbard glacier system, which is the main control on the YSV, covers an area of ~5000 km^2 over a region of the St. Elias Mountains. This area appears to drain the region of maximum relative uplift within the orogeny, with rates that range from 2-4 mm/yr. The Alsek region, in contrast, lies to the east within the Fairweather Fault strike-slip portion of the margin with significantly less exhumation [*Enkelmann et al.,* 2010; *Spotila* and *Berger,* 2010] (Fig. 9). Glacial erosion of areas of rapid tectonic uplift leads to high sediment flux, especially since the mid-Pleistocene transition, as has been documented elsewhere in the Gulf of Alaska [*Berger et al.,* 2008; *Reece et al.,* 2011]. This exhumation driven sediment supply, which is not as pronounced in the ASV region, likely is the main factor in allowing YSV slope progradation over the steep initial morphology of the Yakutat Terrane. Models of continental slope fan development propose that as sediment reaches the shelf edge and remobilizes downward, it will begin to accumulate along the base of a steep slope [*Mohrig et al.,* 1999]. The resulting sedimentation lowers the slope gradient and promotes further deposition at the base of the slope, and over time the fan gradient decreases and captures yet more sediment [*O'Grady et al.,* 2002]. The incipient TMF observed on the YSV slope likely represents the youthful stages of fan development.

6. Conclusions

Geomorphic characterization indicates that only one of the two sea valleys (glacial shelf-crossing troughs) across the Yakutat margin is associated with a likely trough mouth fan (TMF). The building of a TMF off the Yakutat Sea Valley (YSV), but not the Alsek Sea Valley (ASV), is likely due to the much larger sediment supply created by the Malaspina-Hubbard glacial system eroding a region of rapid uplift and exhumation within the St. Elias Mountains.

The paleo-ice stream of the ASV, despite crossing a wide shelf covered with easily eroded sediments, has insufficient sediment supply to overcome the steep initial topography created by the Transition Fault and thus the majority of sediment bypasses the continental slope and continues into the Surveyor Fan in a similar fashion to other steep glaciated margins. The YSV paleo-ice stream, in contrast, drains a region of sufficient size and exhumation to provide enough sediment to begin to build out the margin.

The Yakutat systems discussed represent an end-member of temperate glacial margins where spatial variability in source region tectonics plays an important role in sediment flux to the margin. The observed building of an incipient TMF on a steep transform-fault controlled slope, which elsewhere inhibits slope deposition on the same margin, helps to illustrate the importance of sediment supply in glacial margin development.

Tables

Table 1. Zone gradient summary statistics

	Avg. Gradient (°)	**Median Gradient** (°)	**Maximum Gradient** (°)	**Max. gradient depth** (m)	**Shelf width** (km)	**Slope Width** (km)	**Margin Shape**	**Margin Group**
Zone A	7.7 ± 3.8	7.8	17.2	-2520	71.8	35	Type 1	A1
Slope	8.5 ± 3.1							
Rise	1.2 ± 0.4							
Zone B	7.7 ± 3.5	8.6	13.3	-2620	84.8	30	Type 1	A1
Slope	9 ± 2.1							
Rise	1.4 ± 0.4							
Zone C	15.8 ± 3.5	16.8	33.5	-1640	101.1	10	Type 2	A2, A3
Slope	18.3 ± 7.2							
Rise	1.2 ± 0.5							
Zone D	13.8 ± 8.4	14.6	30.9	-1560	95.7	12	Type 3	A2
Slope	16.4 ± 6.8							
Rise	2.2 ± 1.2							
Zone E	18.1 ± 11.5	16	41.9	-1360	93.1	8	Type 3	A3
Slope	23.5 ± 9.4							
Rise	6.8 ± 4.4							
Yakutat Margin	12 ± 6.4	13.8	22	-1380	-	-	-	-

Table 2. Gully feature summary statistics

	Median Relief (m)	**IQR 25-75%** (m)	**Max. relief** (m)	**Avg. relief** (m)	**Avg. width** (m)	**Avg. gradient** (°)	**Density** (gully/km)	**N=**	**U-shaped** (%)	**Relief Group**
Zone A	29.5	13.7-49	142.8	37.4 ± 30.3	1555 ± 694	9.1	.63	45	36	1
Zone B	20.8	12.9-30.9	216.5	33.1 ± 44.4	2178 ± 1088	9.1	.39	21	40	1
Zone C	98.3	49-141.3	247.3	99.7 ± 64.8	1552 ± 694	16.4	.64	40	15	2
Zone D	65.5	29-117.4	268.1	85.7 ± 64.8	1666 ± 1160	20.6	.58	42	32	2
Zone E	102.3	46.3-129.5	272.4	96.1 ± 59.1	1535 ± 806	37	.64	38	36	2
Overall	52.6	23.6-111.7	268.1	70.1 ±	1667 ±	19.6	.56	186	30	-

Figures

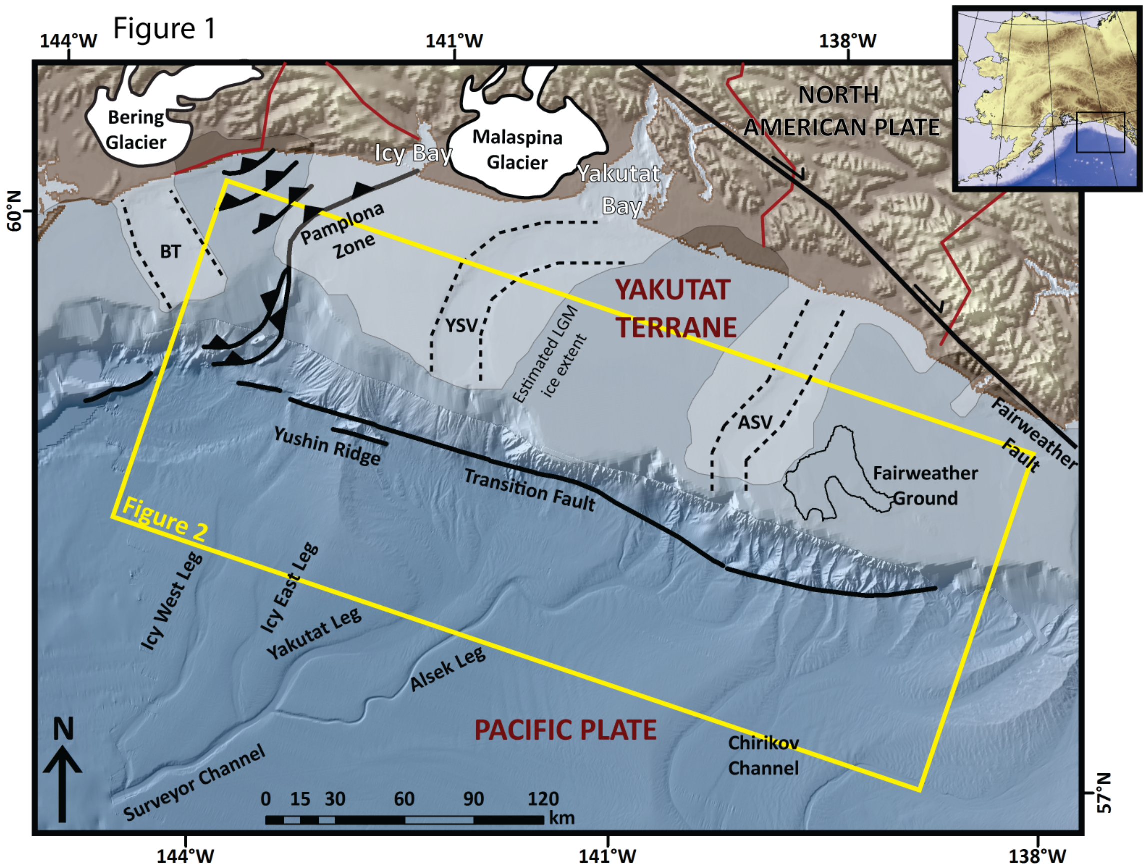

Figure 1. Shaded relief of the northeastern Gulf of Alaska. Major channel systems, glaciers, faults, Last Glacial Maximum (LGM) ice extent and tectonic plate boundaries are labeled. BT- Bering Trough, YSV- Yakutat Sea Valley, ASV- Alsek Sea Valley. [*Gulick et al.,* 2007, 2013; *Manley* and *Kaufman,* 2002]

Figure 2A

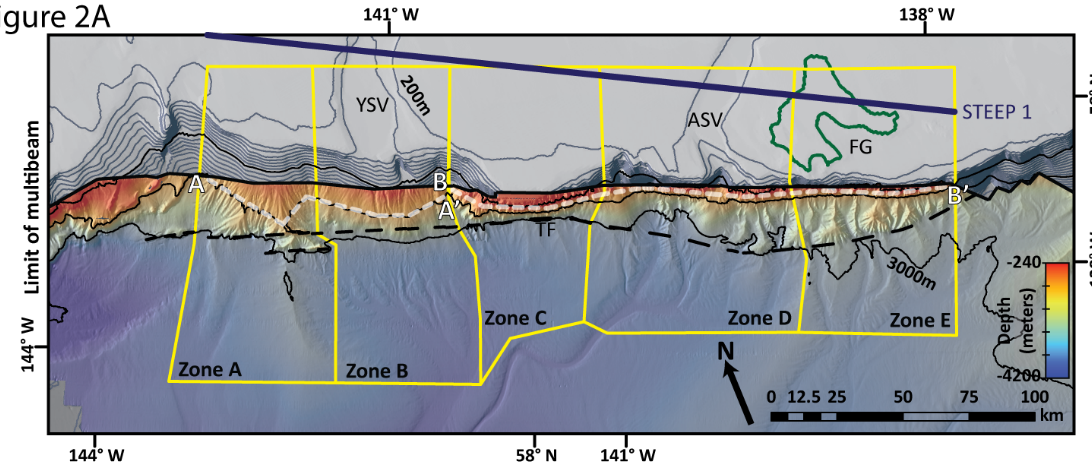

Figure 2B

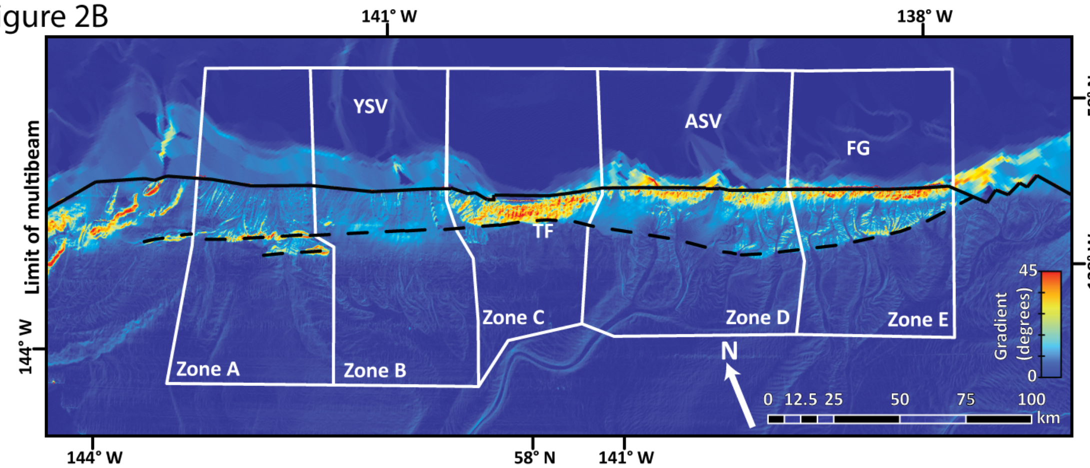

Figure 2. (A) Shaded high-resolution multibeam bathymetry of the Yakutat margin. The large-scale morphologic zones are shown in yellow. Location of the STEEP1 seismic line is indicated in green, while across-slope bathymetric profiles location are in white. Bold black line indicates approximate extent of the Fairweather Ground (FG). Dashed black lines are approximate extents of Yakutat Sea Valley (YSV) and Alsek Sea Valley (ASV). Continental shelf and upper slope blue contour interval is 100m, while black index contours are at a 1000m interval. The depth of the basin floor increases to the west, closer to the trench. **(B)** Calculated seafloor gradient. Warmer colors indicate steeper slopes. Morphologic zone boundaries are shown in white. The seafloor channels draining Zones A, B, and C are much less pronounced than those to the east, with lower gradient channel walls.

Figure 3

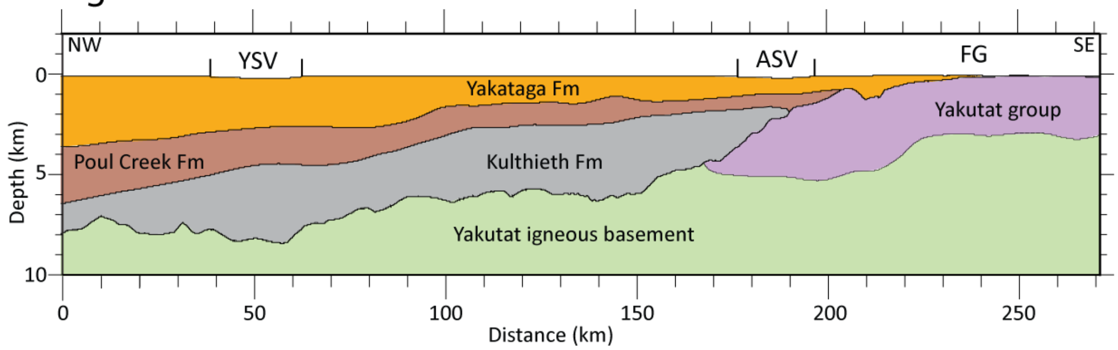

Figure 3. Stratigraphic cross section of the Yakutat Terrane shelf. Yakataga Formation sediments are the first glacially derived material observed. Both the YSV and ASV erode through the Yakataga Formation. Figure adapted from [*Van Avendonk et al.,* 2013]

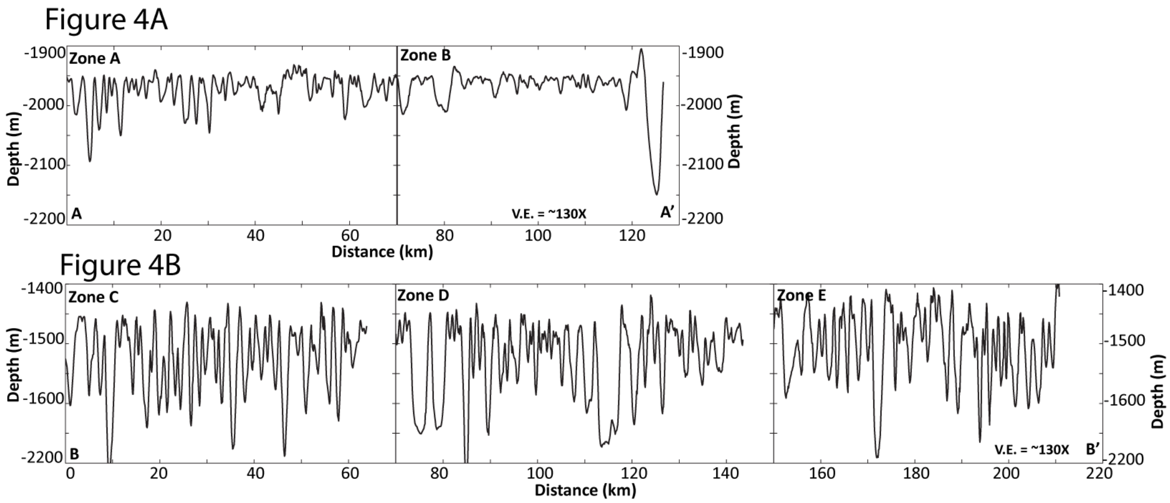

Figure 4. Extracted depth profiles from the mid-slope across the study region. Profile A-A is taken parallel to the 2000m bathymetric contour in zones A and B, while profile B-B follows the 1500m contour in Zones C, D, and E.

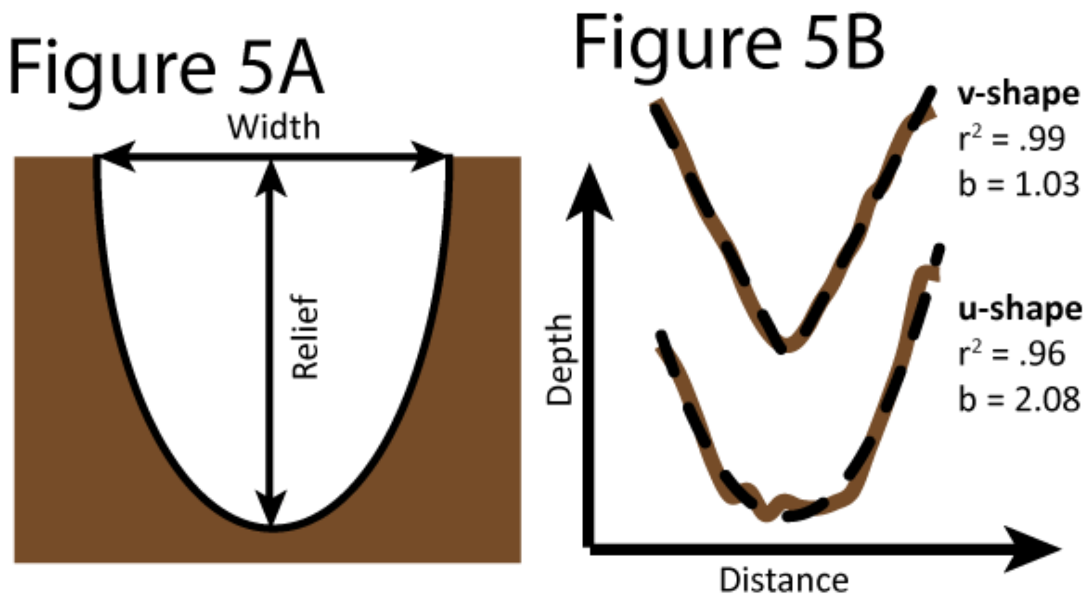

Figure 5. Example of gully parameters extracted from slope bathymetric profile. In shape example of U-shaped and V-shaped gullies, green line indicates actual gully cross section while dashed black line is the best-fit output of the General Power Law (GPL) program. r^2 values and *b* values (Eq. 1) are shown for each fit.

Figure 6

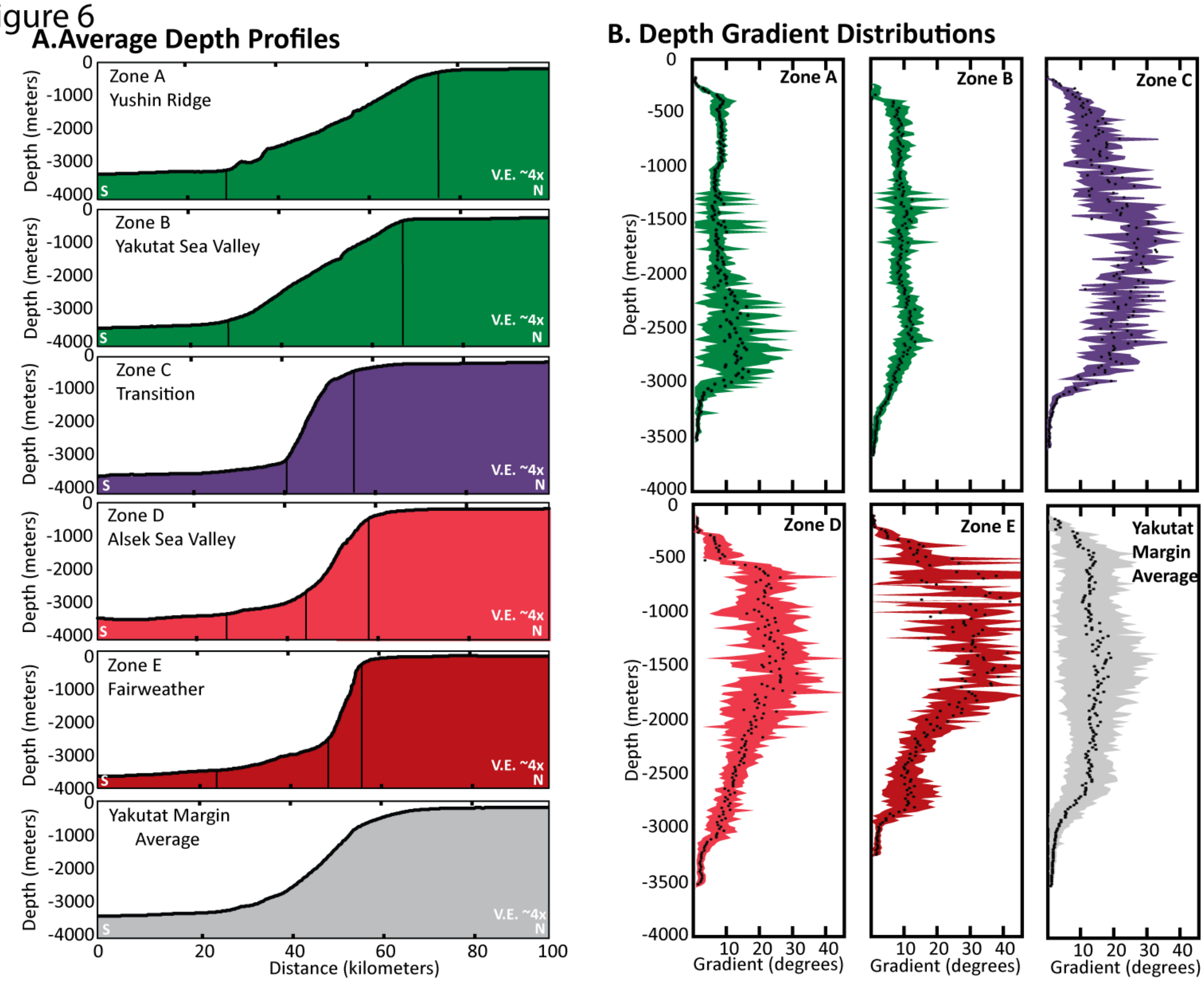

Figure 6. (A) Average depth profile from the continental shelf to the plain for each zone. **(B)** Depth-gradient distributions of each morphology zone. Black dots indicate average gradient of a given 20m depth bin. Shaded region around points indicates +/- one standard deviation. Depth-gradient and depth profile plots are colored according to the factor analysis and ANOVA testing. Green = type 1 shape, purple = type 2, and shades of red = type 3. Identical color indicates no statistical difference in depth-gradient distribution.

Figure 7

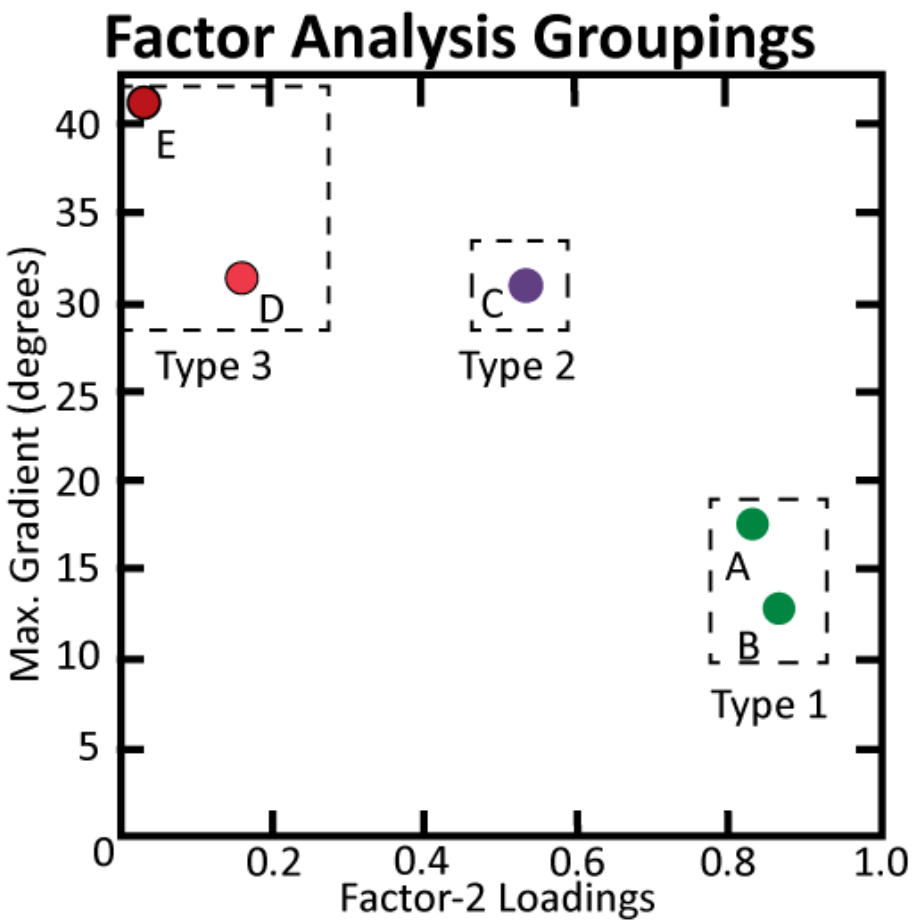

Figure 7. Results of depth-gradient distribution factor analysis. Factor-2 loadings are plotted against maximum gradient of each zone to identify similarity in margin shape [*O'Grady et al*., 2000; *Brothers et al*., 2013].

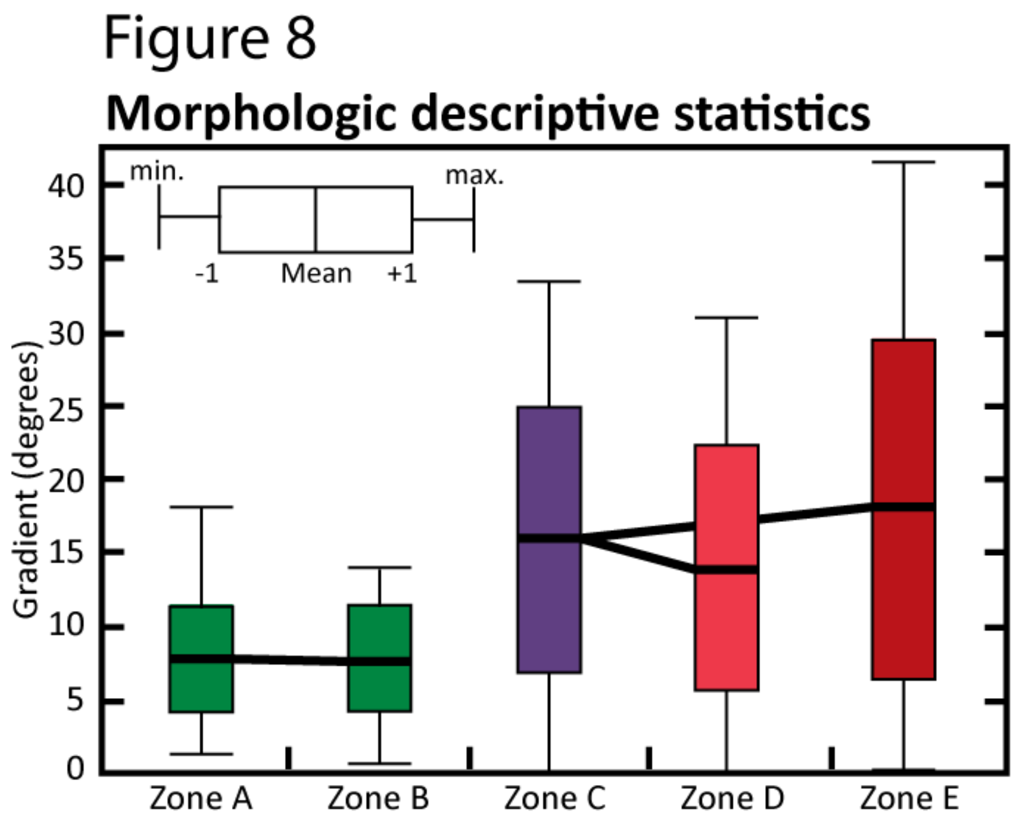

Figure 8. Box plot results of depth-gradient distribution ANOVA testing. Black lines connect means that are not statistically different. Zone C is not significantly different from either Zone D or E.

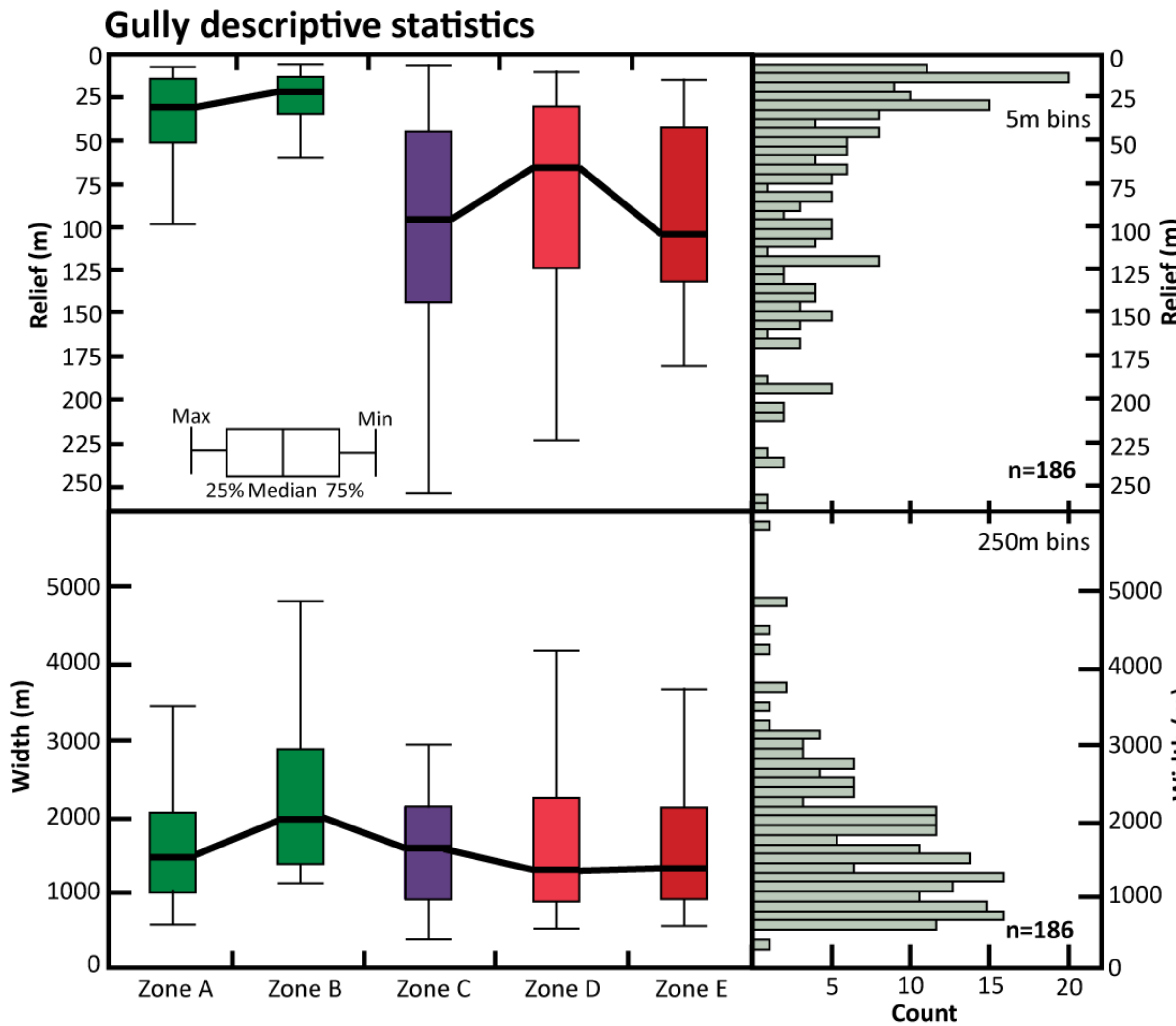

Figure 9. Box plot median values and histograms of gully relief and width by zone. Median values that are not significantly different are connected by bold black line. Gully widths across the entire margin are fairly similar, while Zones A and B relief is much lower than those of Zones C-E.

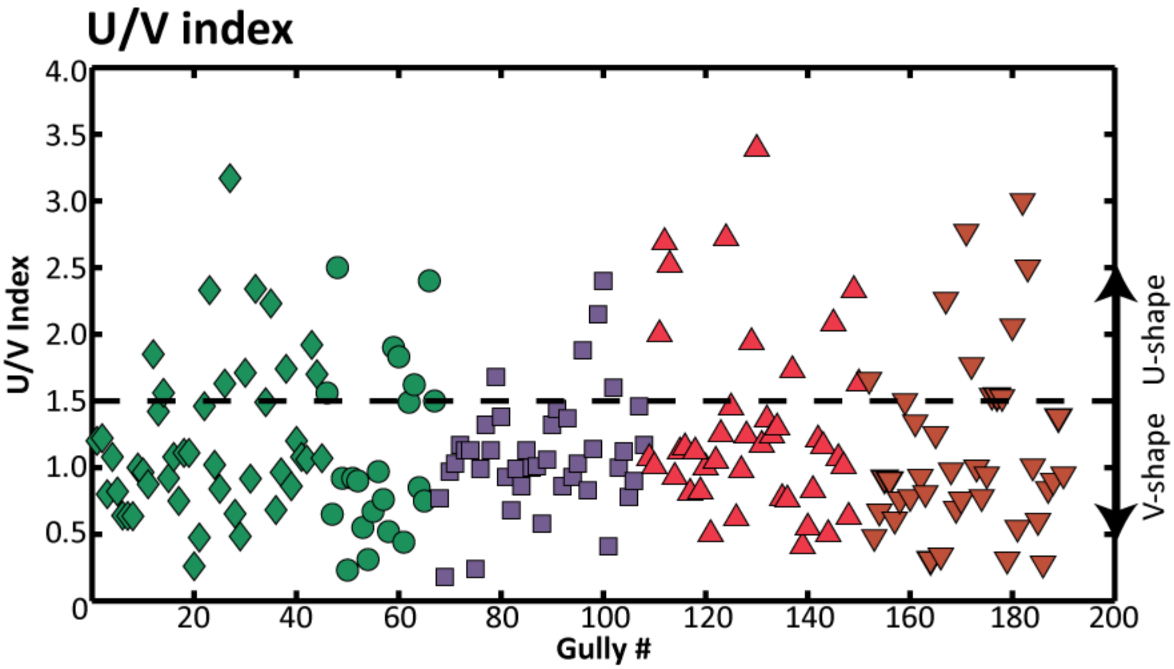

Figure 10. U/V index of all identified slope gullies and channels. Values >1.5 are classified as U-shaped, while values <1.5 are V-shaped.

Figure 11

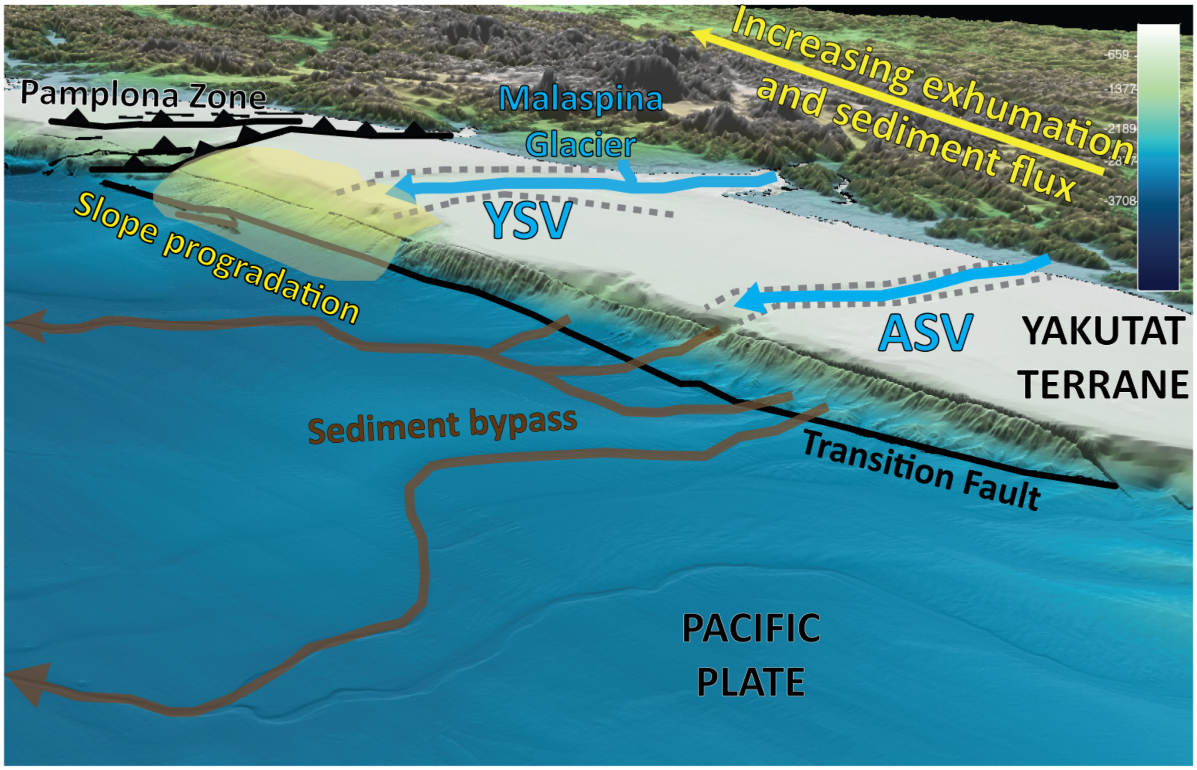

Figure 11. 3D perspective view of the Yakutat Terrane margin. The continental slope in front of the YSV appears to be undergoing recent progradation, while farther to the east sediments routed by the ASV are bypassing the slope and feeding into the Surveyor Fan.

Figure S1

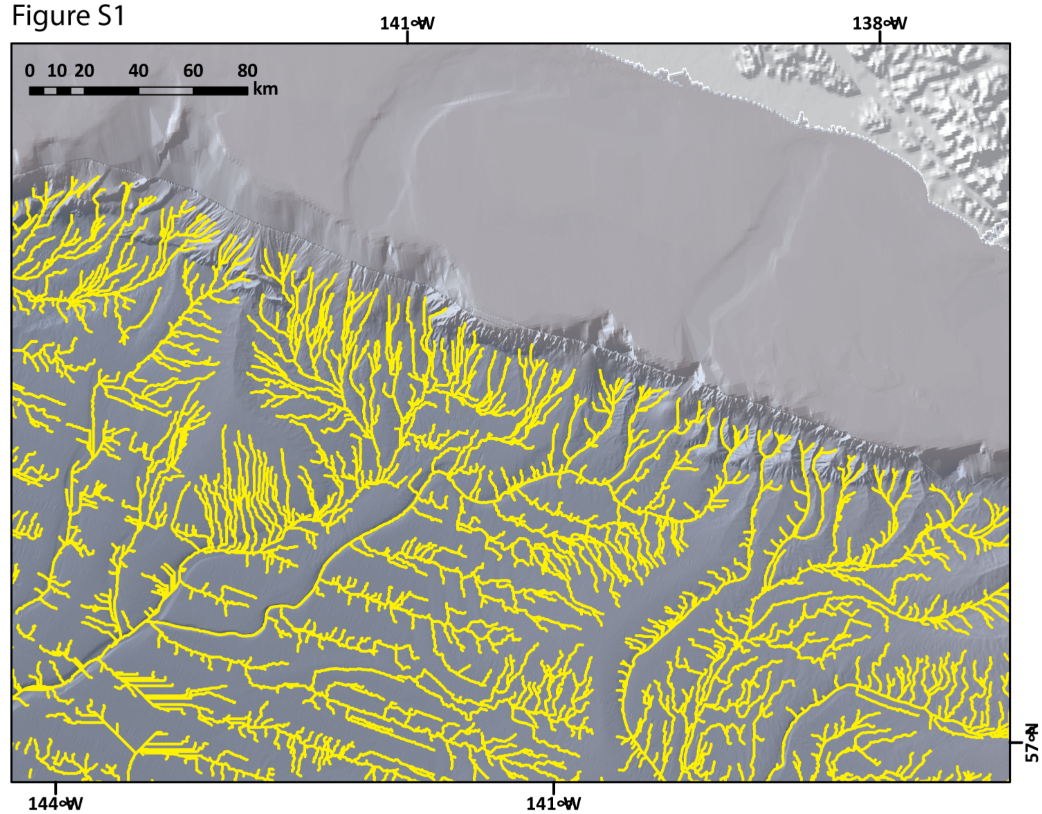

Figure 12. Channel and gully thalweg lines marking regions of maximum flow accumulation.

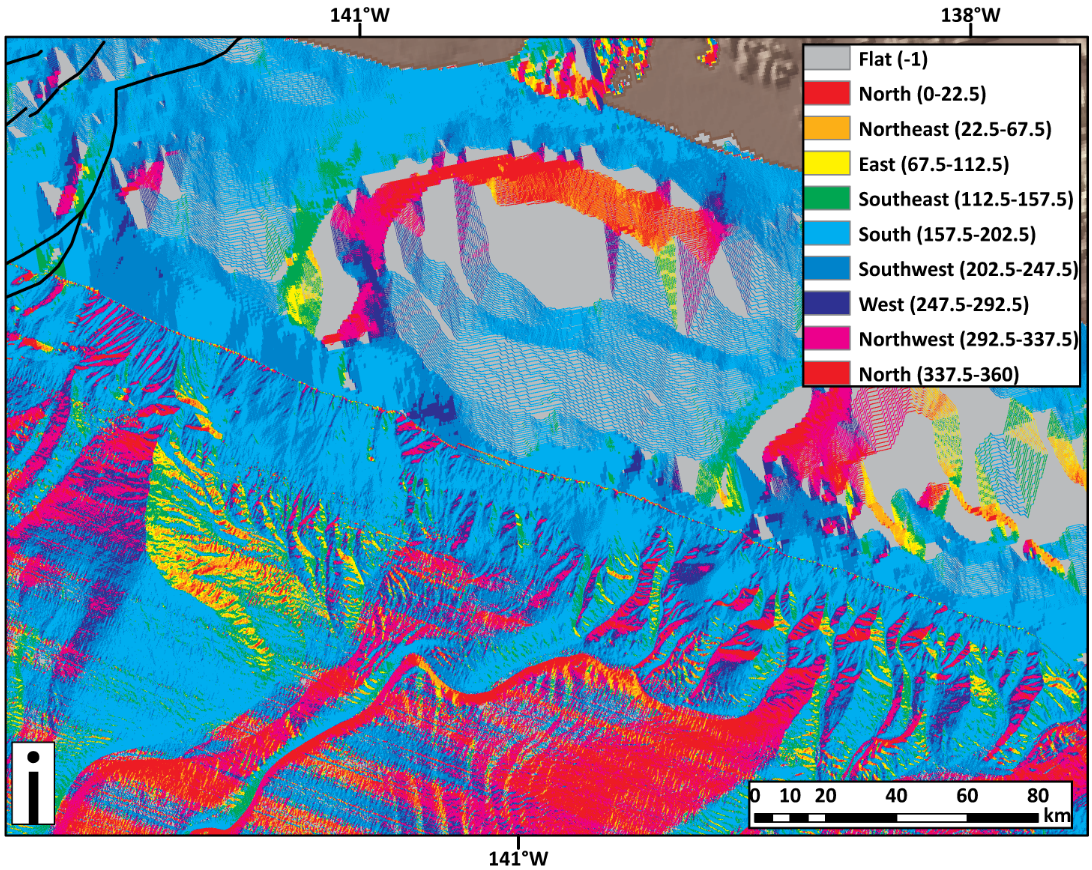

Figure 13. Seafloor aspect map calculated from digital elevation model (DEM). Colors denote compass direction that pixel is oriented towards.

CHAPTER 2: MID-PLEISTOCENE SHELF EDGE GLACIATION IN THE GULF OF ALASKA

Abstract

Temperate glacial systems in the Gulf of Alaska are unique in their interaction with an active orogen, the St. Elias Mountains. This environment has led to climate-tectonic feedbacks and a drastic rate of erosion and sediment deposition offshore. Here we present seismic data showing that the Yakutat continental slope has been aggrading since the onset of glaciation but it is only since the mid-Pleistocene that glaciers have been able reach the continental shelf edge and begin to build a trough mouth fan. We conclude that although marine temperate glaciers have been active in the Gulf of Alaska since the Pleistocene, they were unable to sustain advances to the shelf edge until the mid-Pleistocene climate transition and its associated shift from 41 Kyr to 100 Kyr glacial-interglacial climate cycles. This finding supports earlier studies that found no evidence for sustained ice at the shelf edge with the intensification of northern hemisphere glaciation.

1. Introduction

Ongoing collision of the Yakutat Block with the North American Plate has led to the formation of the active Chugach - St. Elias orogeny, a mountain range with the highest coastal relief in the world [*Pavlis et al*., 2004; *Headley et al*., 2013]. While alpine glaciers have existed since the Miocene in this region, the onset of marine-terminating glaciers sometime in the Pleistocene has led to thick glacial sedimentary deposits on the continental shelf and beyond [*Bruns and Carlson*, 1987; *Eyles et al*., 1991; *Lagoe and Zellers*, 1996; *Worthington et al*., 2010]. Efficient sediment transport to the deep sea has also lead to the growth of the deep sea Surveyor Fan which has been intensely studied as a recorder of climatic events and glacial-tectonic interactions [*Lagoe et al*., 1993; *Rea and Snoeckx*, 1995; *Reece et al*., 2011].

Regional glacial history of the Chugach – St. Elias area can be divided into three intervals, A-C. Glacial interval A begins in the Miocene with alpine glaciation that lead to increased sediment flux and deposition of the Yakataga formation [*Lagoe et al*., 1993]. Glacial interval B starts at the intensification of Northern Hemisphere glaciation at ~2.5-3.0 Ma, or roughly the Pliocene-Pleistocene boundary, when the first ice-rafted debris is found in the distal Surveyor Fan [*Rea and Snoeckx*, 1995; *Shipboard Scientific Party*, 2014]. Glacial interval C begins at ~1 Ma [*Berger et al*., 2008] and is accompanied by a near doubling in sediment accumulation rates in the distal Surveyor Fan [*Rea and Snoeckx*, 1995; *Berger et al*., 2008; *Reece et al*., 2011]. Glacial interval C and its accompanied increase in glacial erosion of the St. Elias orogen encompasses the period after the shift from 41 Kyr to 100 Kyr glacial-interglacial climate cycles known as the mid-Pleistocene Climate Transition (MPT) [*Clark et al*., 2006; *Berger et al*., 2008].

The Yakutat Sea Valley (YSV) is one of eight shelf-crossing troughs found in the Gulf of Alaska that are interpreted to be glacial in origin (Fig. 1) [*Carlson et al*., 1982; *Elmore et al*., 2013]. Approximately 25 km wide and 300m deep at its shelf edge outlet, it has likely acted as the main ice conduit for the Malaspina-Hubbard glacial system during the Last Glacial Maximum as well as several previous advances [*Elmore et al*., 2013]. This system drains one of the most rapidly uplifting areas of the St. Elias orogeny [*Enkelmann et al*., 2010; *Headley et al*., 2013]. The continental slope associated with the YSV has a steep gradient of 5-10°, with the base of slope controlled by the low-motion Transition Fault [*Gulick et al*., 2007, 2013]. However, the slope exhibits prominent outward bulging contours indicative of sediment deposition and progradation [See chapter 1]. Sediment deposits at the mouth of a cross-shelf trough are commonly referred to as a trough mouth fan (TMF), a type of slope sediment deposit usually consisting of debris flows and slides as well as more layered periglacial sediments [*Vorren and Laberg*, 1997; *O'Grady et al*., 2002; *O'Cofaigh et al*., 2012]. Our earlier morphologic analysis indicates that the Yakutat continental slope hosts a TMF in the early stages of development [See chapter 1].

Analysis of the Surveyor Fan has led to the hypothesis that the change in offshore sedimentation observed at glacial interval C necessitates not only active marine terminating glaciers, but also shelf-edge glaciation [*Berger et al*., 2008; *Reece et al*., 2011]. Using industry and academic seismic reflection data in conjunction with industry wells and newly available IODP drilling results, we evidence of the timing of initial shelf-edge glaciation on the Yakutat shelf, further we discuss the potential that in order to transgress the shelf ice streams required the longer duration glacial maxima that followed the MPT.

2. Data and Methods

In order to determine the best estimate of timing for shelf-crossing trough formation and the incipience of a TMF, we used a combination of seismic reflection profiles and high-resolution (100m pixel size) bathymetric data integrated with available industry and Integrated Ocean Drilling Program (IODP) wells. Multibeam surveying conducted in 2005 provides coverage of the lower and middle continental slope along the Yakutat Block [*Gardner et al*., 2006; *Gulick et al*., 2007]. The St. Elias Erosion / Tectonics Project (STEEP) [*Worthington et al*., 2010] acquired 1250 km of 2-D multichannel seismic (MCS) data across the Alaskan continental slope and basin. Extensive shelf coverage is provided by industry data acquired in 1979 by the Western Geophysical Company as part of a 30,400 km^2 hydrocarbon exploration survey and now available through the United States Geological Survey [*Bruns*, 1983, 1985; *Bruns and Carlson*, 1987; *Elmore et al*., 2013].

STEEP data were processed using a band-pass filter, trace balance, outside mute, normal moveout correction, alpha-trim stack, and *f-x* post-stack time migration (Worthington et al., 2010; Gulick et al., 2013). Industry seismic data were processed through post-stack time migration by Western Geophysical Company. The vertical resolution of both datasets is ~25-30m.

Seismic data interpretation was done using Landmark DecisionSpace Desktop. Our analysis of the continental slope includes identifying seismic reflector truncations, erosional unconformities, and identifying changes in sediment character. Regional seismic horizons from [*Worthington et al*., 2010] were mapped across available seismic data coverage and correlated with industry wells and recently obtained academic drilling results from Integrated Ocean Drilling Program expedition 341 [*Shipboard Scientific Party*, 2014].

3. Observations and Interpretations

Seismic reflector horizons H2, H3, and H4 [*Worthington et al*., 2010] were mapped across the continental shelf using the available seismic data grid and tied to both industry and academic wells [*Van Avendonk et al*., 2013; *Shipboard Scientific Party*, 2014] (Fig. 14). These horizons, while present in the continental slope sediment layers, are not conformable to the offshore sequence boundaries of the Surveyor Fan [*Reece et al*., 2011] (Fig. 15). Using a slope perpendicular seismic line, STEEP2, three distinct packages of slope sediments were identified based on changes in seismic reflector geometry and acoustic character. Major erosional surfaces, channels, and troughs were interpreted along the mid continental shelf using industry line FW074. Above horizon H3 numerous erosional features such as tunnel valleys and possible glacial troughs are identified, while below this surface no obvious erosional features can be clearly observed (Fig. 16).

Sediment below H4 appear to be aggradational in nature, draping on top of the pre-existing Yakutat Terrane crust [*Christenson et al*., 2010] with no obvious pinch-outs or truncation (Fig. 15). Well-defined layered sediments begin to downlap on horizon H4 and numerous truncations can be seen within the wedge-shape geometry. Horizon H2 truncates H3 and H4, and the sediments above H2 appear much more chaotic in appearance. Layers above H2 appear lobe shaped, with numerous slumps and slides identified (Fig. 15).

The stratigraphy of industry well OCS Y-0211 is tied to the seismic horizons using the velocity-depth model of *Van Avendonk et al*., [2013]. H4 corresponds with the Yakataga / Poul Creek formation contact, while H3 is an arbitrary reflector slightly above the LO of Neoglobigerina Asanoi at ~2.2 Ma [*Zellers*, 1995; *Worthington et al.,* 2010]. Bering Trough IODP wells U1420 and U1421 both failed to penetrate the 0.781 Ma Bruhnes-Matuyama magnetic reversal. Since horizon H2 is below this boundary, the youngest possible age for H2 is ~300 Kyr [*Shipboard Scientific Party*, 2014].

4. Discussion

Our analysis of Yakutat slope seismic data finds that of the three distinct stratigraphic units overlying the Yakutat terrane crustal basement, only the upper two are glacial in origin. The lowermost unit bounded above by horizon H4 represents a pre-glacial sediment package that was aggrading onto the Yakutat crust, with no visible evidence for progradation (Fig. 15). Based on correlation with industry well OCS-Y0211 this sedimentary unit consists of the Poul Creek and Kulthieth formations, which are mainly fluvial in nature [*Risley et al*., 1992; *Plafker*, 1987; *Van Avendonk et al*., 2013].

Above horizon H4 the observed slope sedimentary units correspond with the Yakataga formation, a ~5km thick unit mainly composed of debris flows, submarine channels, and other glacial sedimentary deposits [*Eyles and Lagoe*, 1990; *Zellers*, 1995]. Although the available seismic data has a relatively coarse resolution, large scale shifts in sedimentary layer dynamics can still be observed. High-amplitude laminated sediments are seen to onlap on horizon H4, indicating a change in sediment accumulation and depositional dynamics (Fig. 15). This shift in slope sedimentation coincides with the beginning of glacial interval A as previously observed by increased sedimentation rates in the Surveyor Fan and glacial character of the Yakataga formation [*Lagoe et al*., 1993; *Reece et al*., 2011].

Horizon H3, which is slightly younger than ~2.2 Ma, was originally interpreted as marking the Plio-Pleistocene transition at 1.8 Ma [*Zellers*, 1995; *Worthington et al*., 2010]. However, the recent geologic time scale revision places this boundary at 2.58 Ma and therefore the Plio-Pleistocene transition must be some distance below H3 [*Gradstein et al*., 2012]. There does not appear to be any significant horizon or change in slope sedimentation in the interval from the base of the Yakataga formation to H3, indicating that no apparent change in slope dynamics occurs with the transition to the Pleistocene. While this is in agreement with no change in sedimentation in the distal Surveyor Fan as compared to glacial interval A (Reece et al., 2011), the proximity of the slope to the glacial source regions within the St. Elias orogeny make slope seismic records more likely to record changes in erosion and sediment transport, and no such change is observed (Fig. 16). Analysis of mid-shelf seismic records find that ice was present and dynamic along the Yakutat continental shelf from at least ~2.2 Ma, as evidenced by numerous troughs, tunnel valleys, and erosional surfaces present above horizon H3 (Fig. 16). Although ice appeared to be present along the inner shelf at different times in the early Pleistocene, there was no associated change in sedimentation at either the continental slope or in the distal fan. Our analysis suggests that ice was either unable to sustain advances to the shelf edge or, more likely, reach it at all.

The most drastic shift in slope sedimentation occurs with horizon H2. Within the slope stratigraphy H2 is an erosional boundary that truncates the older horizons H3 and H4 and extends to the mid-slope, although it is not conformable to the Surveyor Fan sequences (Fig. 15). Sediments above this boundary are much more chaotic, with acoustically transparent and occasional layered units both entrained in a series of slumps and slides. These slides appear to originate near the shelf edge, but can be found at all points on the slope down to the Transition Fault. Although horizon H2 is erosional in nature and has eroded some of the upper pre-existing slope deposits, no evidence exists for any erosional surfaces or preserved slides or debris flows within the slope stratigraphy prior to this point (Fig. 15).

Mapping horizons H2 and H3 within the available seismic grid and correlating to industry and academic wells allows a relative age constraint to be placed on the slope stratigraphy. IODP wells U1420 and U1421 failed to reach the Bruhnes-Matuyama magnetic reversal, and consequently horizon H2 [*Shipboard Scientific Party*, 2014]. This indicates that H2 must be older than ~0.3-0.781 Ma, but younger than the ~2.2 Ma age of H3.

Onshore and offshore studies have both found increases in erosion of the St. Elias orogeny with the ~1 Ma mid-Pleistocene climate transition (MPT), and with it an accompanying doubling of sedimentation rates offshore. These significant changes are likely due to the much longer 100 Kyr glacial cycles that have occurred since the MPT which likely have allowed more sustained glacial advances compared to the earlier 41 Kyr cycles [*Clark et al*., 2006; *Berger et al*., 2008]. The significant erosional unconformity at H2 makes it likely that this horizon and its associated debris flows and slumps were the response at the shelf edge to the glacial intensification of the MPT.

High-resolution bathymetry shows that the continental slope in front of the YSV is covered by numerous gullies, chutes, and debris flows and slides, and has prominent outward bulging contours (Fig. 14) [See chapter 1]. Our available seismic data crosses the slope towards the edge of the YSV, and as such only captures the margin of this glacial slope deposit. Existing models of TMF development emphasize the role of debris flows in building TMFs, with slopes becoming rapidly oversteepened during glacial maxima when ice is able to deliver eroded sediment directly to the continental slope [c.f. *Vorren et al*., 2004; *O'Cofaigh et al*., 2012]. The Yakutat continental slope appears to be a TMF in the early stages of development based on its surficial morphology [See chapter 1]. We propose that this Yakutat TMF only began to form with the MPT, when ice streams were first able to reach and sustain themselves at the shelf edge.

5. Conclusions

While the Yakutat continental slope saw an increase in sedimentation with the onset of glacial interval A in the St. Elias Mountains ~6 Ma ago, the main depositional processes on the slope did not change until relatively recently, likely with the ~1 Ma MPT. The abrupt change to mass wasting and wide-scale slumping is indicative of rapid sediment delivery and oversteepening of the continental slope.

Evidence exists for marine terminating glaciers along the mid-continental shelf since the early Pleistocene, but no obvious coincident change in sediment deposition on the slope is observed. The erosional contact and shift in sedimentary processes likely coincides with the mid-Pleistocene climate transition to 100 Kyr glacial-interglacial cycles. This transition marks the first time that marine-terminating glaciers were able to not only exist, but had sufficient time to advance across the shelf to the shelf edge and begin to build an incipient TMF on the Yakutat continental slope.

Figures

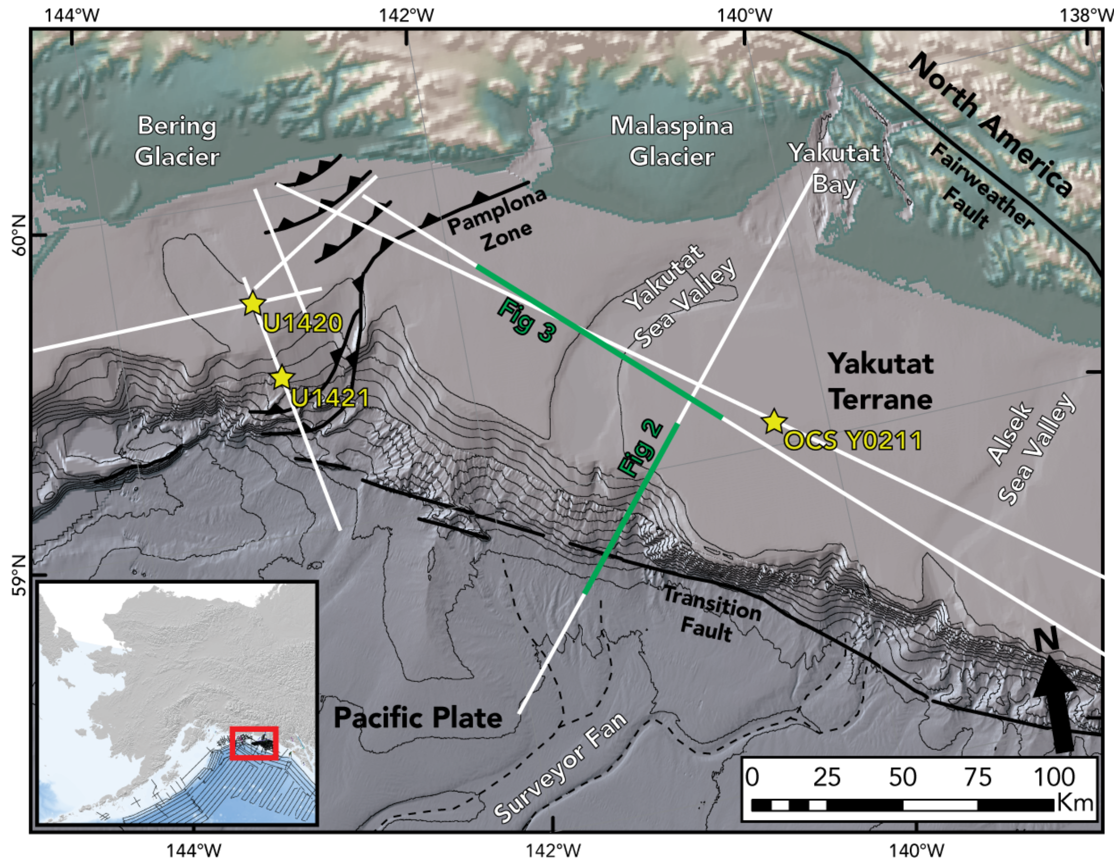

Figure 14. Shaded relief of the northeastern Gulf of Alaska. Glaciers, faults, and tectonic plate boundaries are labeled. Note pronounced bathymetric contour bulges in front of Yakutat Sea Valley and to the west. White lines indicate example seismic lines used for horizon/well correlation. Green lines indicate figure locations. Inset figure shows position of Yakutat block in the Gulf of Alaska, and overall seismic data coverage used in study. [*Gulick et al.,* 2007, 2013]

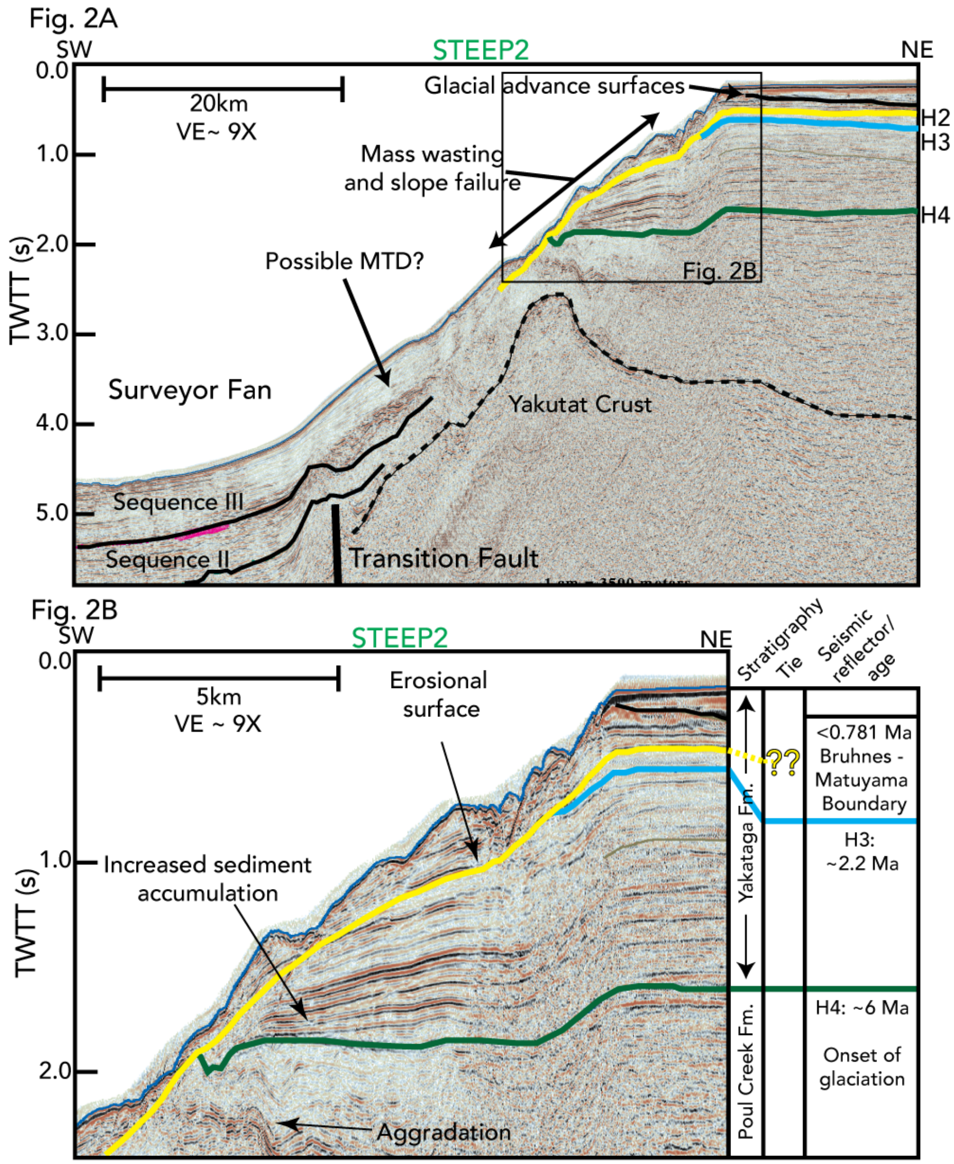

Figure 15. **A)** Multichannel seismic profile crossing the Yakutat slope from southeast to northwest. Seismic reflector horizons H2-H4 are denoted with colored lines as defined in (Zellers, 1995; Worthington et al., 2010). Section inset for figure 2B is shown by black box. **B)** Close in of upper slope of Yakutat block. Horizons H2, H3, and H4 are shown by colored lines. Stratigraphy and approximate ages as defined by (Zellers, 1995; Shipboard Scientific Party, 2014).

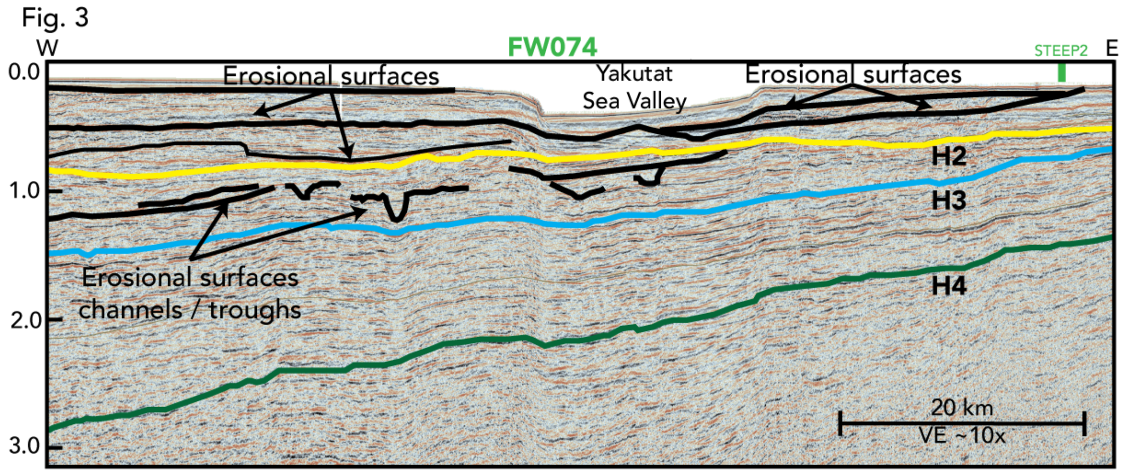

Figure 16. Multichannel seismic profile crossing the Yakutat shelf from west to east. Seismic reflector horizons H2-H3 are denoted with colored lines. Black lines indicate erosional surfaces mapped and interpreted as glacial in origin.

REFERENCES CITED

Alley, R.B., Dupont, T.K., Parizek, B.R., Anandakrishnan, S., Lawson, D.E., Larson, G.J., and Evenson, E.B. (2006), Outburst flooding and the initiation of ice-stream surges in response to cooling: a hypothesis, *Geomorphology*, 75, 76-89.

Atwood, R.J., Bruns, T.R., Carlson, P.N., Molnia, B.F., Plafker, G. (1981). Bathymetric maps of the northern Gulf of Alaska, *US Geological Survey Miscellaneous Field Studies*, Map MF-859. 3 sheets.

Berger, A. L., Gulick, S. P. S., Spotilla, J. A., Upton, P., Jaeger, J. M., Chapman, J. B., Worthington, L. A., Pavlis, T. L., Ridgeway, K. D., Willems, B. A., and McAleer, R. J. (2008), Quaternary tectonic response to intensified glacial erosion in an orogenic wedge: *Nat. Geoscience,* 1, 793-799.

Batchelor, C.L., Dowdeswell, J. A. (2013), The physiography of High Arctic cross-shelf troughs. *Quat. Sci. Rev*., 1–29.

Batchelor, C. L., J. A. Dowdeswell, and J. T. Pietras (2013), Evidence for multiple Quaternary ice advances and fan development from the Amundsen Gulf cross-shelf trough and slope, Canadian Beaufort Sea margin, *Marine and Petroleum Geology*, doi:10.1016/j.marpetgeo.2013.11.005. [online]

Brothers, D.S., ten Brink, U.S., Andrews, B.D., Chaytor, J.D. (2013), Geomorphic characterization of the U.S. Atlantic continental margin. *Marine Geology,* 338, 46–63.

Bruns, T. R., and Carlson, P. R. (1987), Geology and petroleum potential of the southeast Alaska continental margin *in* Scholl, D. W., Grantz, A., and Vedder, J. G., eds., *Geology and resource potential of the continental margin of western North America and adjacent ocean basins*, Volume 6: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, 269-282.

Carlson, P. R., Bruns, T. R., Molnia, B. F., and Schwab, W. C. (1982), Submarine valleys in the northeastern Gulf of Alaska - Characteristics and probable origin, *Marine Geology*, 47, 3-4, 217-242.

Clark, P. U., Archer, D., Pollard, D., Blum, J. D., Rial, J. A., Brovkin, V., Mix, A. C., Pisias, N. G., and Roy, M. (2006), The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric PCO2, *Quat. Sci. Rev.,* 25, 23-24, 3150-3184.

Christeson, G. L., Gulick, S. P. S., van Avendonk, H., Reece, R. S., and Worthington, L. L. (2010), The Yakutat Terrane: Dramatic change in crustal thickness across the Transition fault, Alaska, *Geology,* 38, 10, 895-898.

Dobson, M.R., O'Leary, D., Veart, M., (1998). Sediment delivery to the Gulf of Alaska: source mechanisms along a glaciated transform margin. *Geological Society of London Special Pub,* 129, 43-66.

Dowdeswell, J. A., Evans, J., O Cofaigh, C., Anderson, J.B., (2006). Morphology and sedimentary processes on the continental slope off Pine Island Bay, Amundsen Sea, West Antarctica, *Geol. Soc. Am. Bull.* 118, 606–619.

Dowdeswell, J. A., Ottesen, D., Rise, L., (2006). Flow switching and large-scale deposition by ice streams draining former ice sheets, *Geology*, 34, 313-316.

Dowdeswell, J. A., Cofaigh, C.., Noormets, R., Larter, R.D., Hillenbrand, C.-D., Benetti, S., Evans, J., Pudsey, C.J., (2008). A major trough-mouth fan on the continental margin of the Bellingshausen Sea, West Antarctica: The Belgica Fan. *Marine Geology*. 252, 129–140.

Elmore, C. R., S. P. S. Gulick, B. Willems, and R. Powell (2013), Seismic stratigraphic evidence for glacial expanse during glacial maxima in the Yakutat Bay Region, Gulf of Alaska, *Geochemistry, Geophysics, Geosystems,* 14, 1294-1311

Enkelmann, E., Zeitler, P.K., Pavlis, T.L., Garver, J.I., Ridgway, K.D., (2009). Intense localized rock uplift and erosion in the St Elias orogen of Alaska. *Nature Geoscience*. 2, 360–363.

Gales, J. A., R. D. Larter, N. C. Mitchell, C.-D. Hillenbrand, S. Østerhus, and D. R. Shoosmith (2012), Southern Weddell Sea shelf edge geomorphology: Implications for gully formation by the overflow of high-salinity water, *Journal of Geophysical Research*, *117*

Gales, J. a., Forwick, M., Laberg, J.S., Vorren, T.O., Larter, R.D., Graham, a. G.C., Baeten, N.J., Amundsen, H.B., (2013). Arctic and Antarctic submarine gullies—A comparison of high latitude continental margins. *Geomorphology,* 201, 449–461.

Gardner, J. V., Mayer, L. A., and Armstrong, A., (2006), Mapping supports potential submission to U.N. Law of the Sea. *EOS Transactions American Geophysical Union,* 87, 157-160.

Goff, J.A., (2001). Quantitative classificantion of canyon systems on continental slopes and a possible relationship to slope curvature. *Geophysical Research Letters*, 28, 23, 4359-4362.

Gradstein, F.M., Gabi, O., and Schmitz, M. (Eds), (2012). *The Geologic Time Scale 2012 2-Volume Set*. Elsevier.

Gulick, S.P.S., Lowe, L. a., Pavlis, T.L., Gardner, J. V., Mayer, L. a., (2007). Geophysical insights into the Transition fault debate: Propagating strike slip in response to stalling Yakutat block subduction in the Gulf of Alaska. *Geology*, 35, 763.

Gulick, S.P.S., Reece, R.S., Christeson, G.L., van Avendonk, H., Worthington, L.L., Pavlis, T.L., (2013). Seismic images of the Transition fault and the unstable Yakutat-Pacific-North American triple junction. *Geology,* 41, 571–574.

Harris, P. T., and T. Whiteway (2011), Global distribution of large submarine canyons: Geomorphic differences between active and passive continental margins, *Marine Geology*, 285, 69-86.

Joreskog, K.G., Klovan, J.E., Reyment, R.A., (1976). Geological factor analysis: Amsterdam, Elsevier, 178p

Lagoe, M. B., Eyles, C. H., Eyles, N., and Hale, C., (1993), Timing of Late Cenozoic tidewater glaciation in the far North Pacific: *Geological Society of America Bulletin* 105, 12, 1542-1560.

Lagoe, M.B., and Zellers, S.D. (1996), Depositional and microfaunal response to Pliocene climate change and tectonics in the eastern Gulf of Alaska, Marine Micropaleo., 27, 121-140.

Livingstone, S.J., Cofaigh, C.Ó., Stokes, C.R., Hillenbrand, C.-D., Vieli, A., Jamieson, S.S.R., (2013). Glacial geomorphology of Marguerite Bay Palaeo-Ice stream, western Antarctic Peninsula. *J. Maps* 9, 558–572.

Manley, W., and D. Kaufman (2002), Alaska paleoglacier atlas. Boulder, CO (Inst. Arct. Alp.Res.,Univ.Colorado).http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas/

Micallef, A., and Mountjoy, J.J., (2011). A topographic signature of a hydrodynamic origin for submarine gullies. *Geology,* 39, 2, 115-118.

Noormets, R., Dowdeswell, J. a., Larter, R.D., Ó Cofaigh, C., Evans, J., (2009). Morphology of the upper continental slope in the Bellingshausen and Amundsen Seas – Implications for sedimentary processes at the shelf edge of West Antarctica. *Marine Geology,* 258, 100–114.

O'Grady, D.B., Syvitski, J.P.M., Pratson, L.F., Sarg, J.F., (2002). Categorizing the morphologic variability of siliciclastic passive continental margins. *Geology* 28, 3, 207-210.

O'Grady, D.B., Syvitski, J.P.M., (2002). Large-scale morphology of Arctic continental slopes: the influence of sediment delivery on slope form. *Geol. Soc. London, Spec. Publ*. 203, 11–31.

Ó Cofaigh, C., Dowdeswell, J. a, Evans, J., Kenyon, N.H., Taylor, J., Mienert, J., Wilken, M., (2004). Timing and significance of glacially influenced mass-wasting in the submarine channels of the Greenland Basin. *Mar. Geol*. 207, 39–54.

Ó Cofaigh, C., Dowdeswell, J. a., Allen, C.S., Hiemstra, J.F., Pudsey, C.J., Evans, J., J.A. Evans, D., (2005). Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream, *Quaternary Science Reviews.* 24, 709-740

Ó Cofaigh, C., (2012). Ice sheets viewed from the ocean: the contribution of marine science to understanding modern and past ice sheets. *Philos. Trans. A. Math. Phys. Eng. Sci.* 370, 5512–39.

Pattyn, F., Van Huele, W., (1998). Power law or power flaw? *Earth Surf. Process. Landforms* 23, 761–767.

Plafker, G., Moore, J. C., and Winkler, G. R., (1994), Geology of the southern Alaska margin, *in* Plafker, G., and Berg, H. C., eds., *The geology of Alaska, Volume G-1*: Boulder, Colorado, Geological Society of America, 389-449.

Powell, R. D., and Cooper, J.M. (2002), A glacial sequence stratigraphic model for temperate, glaciated continental shelves, *Geological Society, London, Special Publications* 203

Pudsey, C.J., Camerlenghi, A., (1998). Glacial-interglacial deposition an a sediment drift on the Pacific margin of the Antarctic Peninsula. *Antarct. Sci.* 10, 286–308.

Raymo, M. E., (1994), The initiation of Northern Hemisphere glaciation: *Annual Review of Earth and Planetary Sciences* 22, 353-383.

Rea, D. K., Basov, I. A., and others, (1993), Initial reports, Ocean Drilling Program, Leg 145, College Station, Texas, Ocean Drilling Program.

Rea, D.K., and Snoeckx, H., (1995), Sediment fluxes in the Gulf of Alaska: paleoceanographic record from site 887 on the Patton-Murray seamount platform, *in* Rea, D. K., Basov, I. A., Scholl, D. W., and Allan, J. F., eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, Volume 145: College Station, Texas, Ocean Drilling Program, p. 247-256.

Reece, R.S., Gulick, S.P.S., Horton, B.K., Christeson, G.L., Worthington, L.L. (2011), Tectonic and 643 climatic influence on the evolution of the Surveyor Fan and Channel system, Gulf of Alaska, *Geosphere*, 7, 644, p 830-844

Solheim, A., Faleide, J.I., Andersen, E.S., Elverhøi, A., Forsberg, C.F., Vanneste, K., Uenzelmann-Neben, G., Channell, J.E.T., (1998). Late Cenozoic Seismic Stratigraphy and Glacial Geological Development of the East Greenland and Svalbard–Barents Sea Continental Margins. *Quat. Sci. Rev*. 17, 155–184.

Stokes, C.R., Clark, C.D., (2001). Palaeo-ice streams. *Quat. Sci. Rev*. 20, 1437–1457.

Stokes, C.R., Clark, C.D., Winsborrow, M.C.M., (2006), Subglacial bedform evidence for a major palaeo-ice stream and its retreat phases in Amundsen Gulf, Canadian Arctic Archipelago. *Journal of Quaternary Science* 21, 4, 399-412.

Spotila, J. A., and Berger, A. L., (2010), Exhumation at orogenic indentor corners under long-term glacial conditions: Example of the St. Elias orogen, Southern Alaska, *Tectonophysics* 490, 3-4, 241-256.

Tukey, J.W., (1977). Exploratory data analysis.

Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J. a., Kenyon, N.H., Mienert, J., Rumohr, J., Werner, F., (1998). the Norwegian–Greenland Sea Continental Margins: Morphology and Late Quaternary Sedimentary Processes and Environment. *Quat. Sci. Rev*. 17, 273–302.

Van Avendonk, H.J.A., Gulick, S.P.S., Christeson, G.L., Worthington, L.L., Pavlis, T.L., Ridgway, K.D., (2013). Subduction and accretion of sedimentary rocks in the Yakutat collision zone, St. Elias orogen, Gulf of Alaska. *Earth Planet. Sci. Lett.* 381, 116–126.

Welch, B.L., (1951). On the comparison of several mean values: An alternative approach. *Biometrika* 38, 3-4, 330-336.

Worthington, L.L., Gulick, S.P.S., Pavlis, T.L. (2010), Coupled stratigraphic and structural evolution of a glaciated orogenic wedge, offshore St. Elias Orogen, Alaska, *Tectonics*, 29,

Worthington, L.L., Van Avendonk, H.J. a., Gulick, S.P.S., Christeson, G.L., Pavlis, T.L., (2012). Crustal structure of the Yakutat terrane and the evolution of subduction and collision in southern Alaska. *J. Geophys. Res*. 117, B01102.